Transformability of Existing Buildings:
An Approach based on BIM Technologies

Dissertation

submitted to and approved by the

Department of Architecture, Civil Engineering and Environmental Sciences
University of Braunschweig – Institute of Technology

and the

Department of Civil and Environmental Engineering
University of Florence

in candidacy for the degree of a

Doktor-Ingenieur (Dr.-Ing.) / Dottore di Ricerca
in Processes, materials and constructions in civil and environmental engineering and for the protection of the historic-monumental heritage*)

by

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Submitted on	11 September 2014
Oral examination on	07 November 2014
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2015

*) Either the German or the Italian form of the title may be used.

ABSTRACT

"Towards the automated assessment of re-design concepts for building heritage" is the result of doctoral research inspired by the recent trend of using Information Technologies (IT) tools for architectural design, whose causes and possible evolutions are being studied by academics, researchers and scholars using many different approaches.

Working on an **existing building** represents a complex design challenge that stimulates the development of new experiences and experimental new approaches. With historical buildings it is especially important to reason with and respect the pre-existing "constraints" of composition. In fact, it is possible to "read" precise traces and specific rules of aggregation that do not vary across homogenous categories of building typology.[1]

The building can maintain its native function or change it radically, can retain the original distributive path or have an alternative layout, can respect the existing structure or acquire new additional elements. In any case, during this process of transformation, the final result must balance respect for historical constraints alongside the creative process, whilst avoiding the violation of the principles of sustainable design (from the economic, social and environmental points of view).

From this perspective comes the idea **to study the potential and the limitations of the use of modern IT tools in the context of re-designing existing buildings**.

One possible approach is suggested by "Building Information Modeling" (BIM), which is becoming a new paradigm for the entire architectural, engineering and construction industries. This powerful tool has radically changed the course of design, particularly when clients have complex ongoing programmatic requirements.

BIM may be partially adopted for an automated procedure of assessment: the building can be parameterized, according to the level of detail that is needed, then physically and mathematically analysed. The parametric model can be explored and interrogated in order to gain important information that can be used by the designer throughout the decision-making process.

[1] An 18th-century hospital, for instance, shares particular ratios (between spaces, dimensions of openings, rules about the aggregation of space, and so on) with many other building types such as universities, schools, libraries and public buildings in general.

Although an in-depth review of the literature shows a richness of design methods for new construction, the methods and tools available for dealing with existing buildings are limited.

Starting from the highest level international guidelines concerning BIM implementation (Federal Government's General Service Administration – GSA, USA; COBIM 2012, UK; COBIe 2012, PAS 1192, UK; Senatte BIM Guidelines, Finland; etc.), a series of limitations arise regarding the applicability of BIM in existing contexts that require a general review of the processes and the elaboration of specific software for supporting the design phase.

This thesis will propose a method that integrates Graph Theory with the evaluative process, with particular reference to the circulation aspect within a distribution layout. Using a custom tool that can extract data from a BIM model (rooms and connections from a Revit file) and create a graph from this information, it was possible to measure parameters and define a minimum performance usage as a criterion for comparatively evaluating several design solutions.

ABSTRACT

"Der Weg zu automatisierten Bewertung von Restrukturierungsentwürfen von historischen Gebäuden" ist das Ergebnis einer wissenschaftlichen Forschungsarbeit, inspiriert von dem aktuellen Trend Werkzeuge aus der Informationstechnologie (IT) für den architekturellen Entwurf einzusetzen, dessen Ursachen und mögliche Entwicklung von von Wissenschaftlern, Forschern und Gelehrten auf verschiedenste Weisen untersucht wird.

Die Arbeit an einem **bestehenden** Gebäude stellt eine komplexe Herausforderung hinsichtlich des Entwurfs dar, wodurch die Entwicklung neuer Ideen und experimentierfreudiger Ansätze angeregt wird. Im Umgang mit historischen Bauten ist es von besonderer Bedeutung sich die Rahmenbedingungen der existierenden Komposition zu vergegenwärtigen und diese zu berücksichtigen. Tatsächlich ist es möglich Anhaltspunkte und spezifische Regeln der Zusammensetzung zu identifizieren, die innerhalb einer einheitlichen Gebäudetopologie nicht variieren.[2]

Die ursprüngliche Funktion des Gebäudes kann erhalten bleiben oder radikal geändert werden; ebenso kann die originäre Aufteilung beibehalten oder ein alternatives Layout gewählt werden; die bestehende Struktur kann berücksichtig werden oder neue Elemente aufnehmen. In jedem Fall muss das finale Ergebnis dieses Transformationsprozesses einen Kompromiss aus Achtung vor den historischen Rahmenbedingungen und dem kreativen Prozess darstellen, wobei nicht gegen die Prinzipien des nachhaltigen Bauens verstoßen werden sollte (aus ökonomischen, sozialen oder Umweltschutzgesichtpunkten).

Aus dieser Perspektive entstammt die Idee **das Potential und die Grenzen von modernen IT-Werkzeugen im Kontext der Umgestaltung bestehender Gebäude** zu untersuchen.

Ein möglicher vom "Building Information Modeling" (BIM) verfolgter Ansatz, entwickelt sich zu einem neuen Paradigma für die gesamte Architektur-, Ingenieur- und Bauindustrie. Das leistungsstarke Tool hat zu einer radikalen Richtungsänderung im Entwurf geführt, vor allem dann wenn die Kunden sehr komplexe andauernde programmatische Anforderungen haben.

In teilen kann BIM für die automatisierte Beurteilung herangezogen werden: Entsprechend des benötigten Detailgrades kann das Gebäude parametrisiert werden und

[2] Ein Krankenhaus aus dem 18ten Jahrhundert beispielsweise teilt verschiedene Verhältniswerte (Zwischenräume, Dimensionen, Öffnungen, Vorschriften für die Zusammenlegung von Räumen, etc.) mit vielen anderen Typen von Gebäuden wie beispielsweise Universitäten, Schulen, Bibliotheken und allgemein öffentlichen Gebäuden.

anschließend physikalisch und mathematisch untersucht werden. Das parametrisierte Modell kann analysiert und nach wichtigen Informationen, die dem Designer im Entscheidungsprozess zweckdienlich sind durchsucht werden.

Obwohl eine eingehenden Sichtung der Literatur zeigt, dass eine großen Zahl an Entwurfsmethoden für Neubauten existieren, so ist die Anzahl an Methoden und Werkzeuge für den Umgang mit bestehenden Gebäuden dennoch begrenzt.

Ausgehend von den übergeordneten internationalen Richtlinien für die Implementierung von BIM (Federal Government's General Service Administration – GSA – USA; COBIM 2012, UK; COBIe 2012, PAS 1192, UK; Senatte BIM Guidelines, Finnland, etc.), ergeben sich eine Reihe von Einschränkungen in Bezug auf die Anwendbarkeit von BIM im Bestand, woraus sich der Bedarf nach einer generellen Überprüfung der Prozesse und der Erarbeitung spezifischer Software für die Unterstützung der Design-Phase ergibt.

Diese Arbeit stellt eine Methode vor bei der die Graphentheorie in den Bewertungsprozess integriert wird, wobei besonderer Bezug auf den Zirkulationsaspekt und das Verteilungslayout gelegt wird. Unter Einsatz eines speziellen Werkzeugs das Daten aus einem BIM-Modell (Räume und Verbindungen aus einer Revit-Datei) und einen Graphen aus diesen Informationen erstellt, war es möglich Parameter zu bestimmen und ein Minimum für Nutzung zu definieren, das als Kriterium für den Vergleich von verschiedenen Entwürfen herangezogen werden kann.

ACKNOWLEDGMENTS

My PhD thesis could not have been written without the help and support of numerous teachers, colleagues, researchers and friends involved in various aspect of the work. This work is based on the research activity carried out at DICeA (Department of Civil and Environmental Engineering of the University of Florence), IRMB (Institute of Computational Modelling in Civil Engineering of TU Braunschweig) and the Design LAB (University of Salford) from 2011 to 2014.

Foremost, I wish to thank my family and Francesca for their tolerance and for helping me overcome all the critical moments that I have faced during this time.

Special thanks go to my supervisors: in particular, I would like to acknowledge Prof. Carlo Biagini, with whom I have worked for a long time, Prof. Pietro Capone, who gave me precious encouragement to follow my passion for design, and Manfred Krafczyk, who gave me important suggestions on how to tackle research from different points of view. I would like also to mention Prof. Franco Nuti, the founder of our research.

In addition, I have to thank Dr. Simone Saraceni, who helped me in writing and debugging the code. Without his support it would not have been possible to achieve these results.

I also wish to acknowledge my gratitude to: the institute iRMB of TUBS, with particular thanks for the support of Ehsan Goraki, Jannis Linxweiler and Maik Stiebler; Prof. Volkwin Marg and Arch. Robert Friedrichs of GMP Architekten, who gave me opportunities to work on large scale projects and understand the issues of architectural design; Liam Brady of Manchester City Council and Graham Cavanagh of Ryder Architecture, for giving me access to the documentation about the renovation of Manchester City Library; Arto Kiviniemi of the University of Liverpool and Riccardo Balbo of IED Turin, for their important suggestions about BIM during my stay in Salford; Ricardo Codinhoto of the University of Salford and Alejandro Veliz, for their valuable input on how to tackle international research; the staff of the “Design Lab” and “Think LAB” of the School of the Built Environment from the University of Salford.

Thanks must also go to the students of the University of Florence who have shared the path of BIM with me (Marta Andreani, Filippo Mallo, Davide Pellis and Nora Facchini).

CONTENTS

List of Figures

List of Tables

List of Charts

1 Introduction

Building activity is a process that has gradually become more complicated due to the influence of several factors. The complexity of the architectural product, the number and different specializations of the operators or actors involved, the increasing demands of regulatory, procedural and technical prescriptions, and the increasing lack of time are just some examples of this complexity.

In current professional practice this often means that the first solution proposed is given priority, as it is deemed an acceptable basis for developments. Any alternative hypotheses, even if promising and innovative, are neglected as they would initially involve longer times or greater design costs – at precisely the key moment in the design approach when it would be appropriate to explore different solutions. This gives rise to the need to use other forms of design process management that will facilitate matters and save time.

As in other sectors, the attempt to find more efficient systems for managing design complexity in building has attracted the attention of the scientific community for a number of years. It has led to the introduction of methods and techniques of project planning and control in industrial, mechanical and manufacturing design.

In general it is assumed that the building process is subdivided into "phases", each involving certain "actors" who have their own specialist skills. In this sense the project is the outcome of collective decisions and is hierarchically managed by one or more actors. The intrinsic nature of design in architecture is embodied in its multidisciplinary and interdisciplinary nature and the consequent complexity of the design problem, regardless of the project dimensions and the disciplinary areas involved.

Over the last 20 years research has been conducted to understand and identify the relationship between architectural and building design and the more advanced ICT methods, techniques and tools which have been specifically designed to improve the efficiency of the collaborative design method.

Collaborative design, within the assigned time frame, allows the field of exploration to be extended, with choices being made explicit and their technical-scientific aspects being examined in greater detail in the early phases of the design process. It also enhances the operational efficiency of design development in the concluding phases.

1.1 Research methods in architecture

Using the scientific method to explore architecture seems to offer possibilities beyond the formalist approach. Many descriptions and interpretations of the scientific method can be found and they refer to a body of techniques for investigating phenomena, acquiring new knowledge or correcting and integrating previous knowledge. To be termed scientific, a method of inquiry must be based on gathering observable, empirical and measurable evidence subject to specific principles of reasoning.

In adopting this approach, this thesis starts with a generic investigation of the phenomenon of interest, focusing on a proposed solution. The work follows an approach that can be described as a "Scientific simplified methodology based on inductive procedure",[3] as shown in Figure 1.

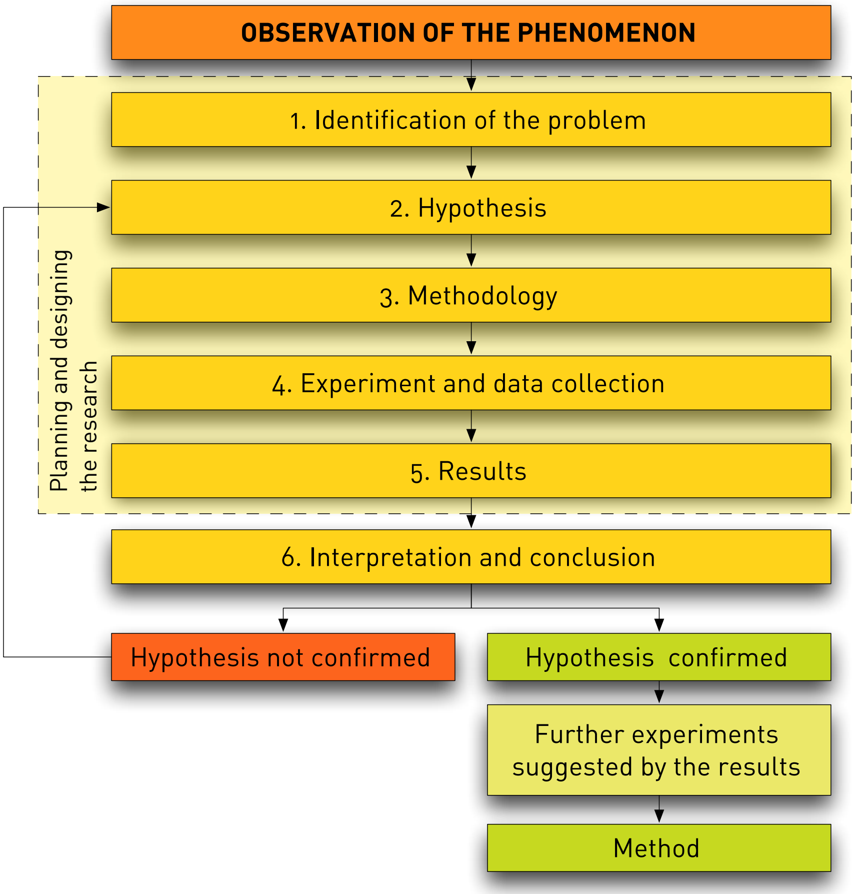

Figure 1 – Scientific simplified methodology based on inductive procedure

[3] Holland et al., 1989.

Observation of the phenomenon

Modern ICT has radically changed the approach to design; in particular BIM is becoming a new paradigm for the AEC industry to reduce the typical mistakes of 2D paper-based management of the procedures, making them easier to control and analyse.[4] BIM can improve the overall process, but its usage is more widespread in the phases after the tender has been awarded. BIM adoption is not yet common in the earlier stages.[5]

Identification of the problems

(1) In a traditional design approach, the first solution proposed is often the privileged idea and is proposed as a basis for further developments. This fact does not allow the potential exploration of an alternative hypothesis for a more appropriate design solution.[6]

(2) In the context of existing buildings and in particular in sedimented historical fabrics the process of transformation has to be managed carefully: only sustainable projects that will not endanger or irreversibly destroy the cultural significance represented by the building are permitted.[7]

Hypothesis

The process of re-designing the concept for an existing building using modern ICT tools could present new research and professional scenarios. Considering that BIM brings benefits across the whole building process for a new construction,[8] is it possible to achieve the same benefits for the re-design of existing buildings?

Research questions

1) Which tools can be integrated into a BIM to confirm the design solution proposal?
2) Can Graph Theory support a BIM-based process?
3) Which parameters have to be taken into account in the constitution of a BIM?
4) Which issues are checked from BIMs using model-checking tools?
5) Which are the main model-checking tools currently available?
6) Are there case studies on this issue? What is the level of maturity in adopting BIM in other countries?

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[4] Eastman et al., 2011.

[5] Penttilä, 2007.

[6] Kalay, 2004.

[7] Roders & Hudson, 2012, p. 175.

[8] Eastman et al., 2011, p. 19.

From these questions, it was possible to begin the overall research process. Following a complex literature review, trends, methods and software for dealing with the renovation of existing buildings were highlighted.

Objectives

1) Highlight the potential and limitations for BIM implementation in the context of existing buildings, with particular reference to the re-design phase, using the "model checking" procedure;

2) Implement (through a semi-automatic procedure) a method which allows for the evaluation of a design solution through both quantitative and qualitative factors in a deterministic approach.

Methodology

The methodology (see Chapter 4) is based on a "**case based research**" process that is subdivided into two phases:

1) Theoretical, mainly dedicated to the definition of the rules and criteria for the evaluation of a design solution;

2) Practical, which concerns the implementation of the criteria previously defined and applied, through the use of specific programming languages for processing BIM models and gathering data.

For the former, the following will be defined:

1) Rules and criteria;

2) How to use Graph Theory;

3) Definition of the performance of a design solution.

The last of these, for the practical approach, is dedicated to pure implementation through specific software. A standalone plug-in was developed to read the IFC file, as was a plug-in for Revit Autodesk. Moreover, using this software for the model checking[9] made it possible to create specific rules in an appropriate format before proceeding to an automated assessment of the design solution.

Measuring the performance of a design solution can be proposed through an implementation of existing software. All the rules and data were validated using examples and relevant scenarios (see Chapter 5).

[9] Solibrì Model Checking v.9, produced by Solibrì, is one possible software for the model checking that was used in this thesis.

Tools

1) BIM tools (Autodesk Platform);
2) SDK for Revit Autodesk;
3) MATLAB R2011b;
4) Solibrì Model Checker – IFC;
5) Microsoft Studio 2010 (programming C#).

Expected results

1) Achieve a method for evaluating design solutions using a definition of "performance" that is based on quantitative and qualitative data;
2) Through the software, allow designers to improve the overall quality of design.

1.2 Research hypothesis

In a traditional design approach, the first solution proposed is usually the privileged idea and serves as a basis for further developments. This fact does not allow for the potential exploration of an alternative hypothesis to find a more appropriate design solution. Especially in the context of existing buildings, and in particular in sedimented historical fabrics, the process of transformation has to be managed carefully: only sustainable projects that will not endanger or irreversibly destroy the building's cultural significance are permitted.

The process of re-designing the concept for an existing building using modern IT tools could present many new research opportunities and professional scenarios. Considering that BIM brings benefits across the whole building process for a new construction, the challenge here is to verify if the same benefits could be achieved in the re-design of existing buildings.

From a thorough analysis and a careful review of the literature, several issues emerge concerning the implementation of BIM in the re-design of existing buildings. We can highlight the following main points:

1) Choice of the best survey technology to represent 3D artefacts and level of detail of BIM models;
2) In the early designs the project has to be manipulated in a simplified abstract state, in contrast with the high level of detail provided by a BIM model;
3) The absence of a suitable taxonomy for historic buildings, which involves problems of interoperability and easy sharing of information between IFC.

In the first point (1), dealing with a historic building often means addressing several difficulties which arise during the early survey stages. Some methods, defined as "reality-based",[10] only allow partial information exchange. Textured 3D models can share only dimensional and visual information when representing complex architectural sites,[11] and not allow further types of analysis. It may be possible to store information in a database

[10] This is based on a "rendering" representation and the use of raster graphics. Through the use of texture it is possible to represent any surface of an object with the computer. Flat shading, texture mapping, bump mapping, transparency, ray trace and radiosity are some examples of characteristics that could be manipulated to achieve a similarity with reality. More information can be found in the work of Manfredini and Remondino (Manferdini & Remondino, 2010).

[11] Remondino, 2011.

and link historical sources to the three-dimensional model,[12] which can also be achieved using a point-cloud.[13] Instead, BIM technology can enrich the three-dimensional model with other data to enable a process of management, modification and analysis for a better intervention proposal. It is evident that the next implementation will be to merge the representation capability of a 3D object offered by the Computer Graphic into a platform (probably defined as BIM with some variations) which can perform analysis and gather data.

Regarding the second point, there are two fundamental problems connected with adopting BIM during the early design phase. Firstly, the high level of detail provided by the sophisticated software, which is unnecessary in this phase, is perceived as a limitation by users. Secondly, depending on what strategy and software the project team adopts, it may be necessary to implement significant changes in the relationships between project participants and the agreements between them.[14]

This latter aspect, related to software compatibility issues, raises one of the most complicated problems, and one that can only be partially solved. For instance, before starting the design process, the work team is called upon to declare which kind of specialist software will be adopted and the ways in which files are to be exchanged. In this context the user can adopt a specific BIM platform belonging to the same software company, which ensures interoperability between proprietary exchange formats or, instead, use the IFC format file, a non-proprietary and open file format.[15] Although use of the IFC file has partially democratized the adoption of the BIM software, the technical aspects cannot be considered as the only solution for the success of the project.

Regarding the third point, in order to ensure interoperability between Building Object Models (column, capitals, frames, tympanum, etc.) we must create a standard nomenclature for historic buildings that must be recognized by all BIM platforms. This requires: (i) a classification of objects, (ii) naming conventions, (iii) the definition of a semantic structure of historic building attributes and (iv) rules concerning topological interference between parametric objects (for instance, we can consider the topological relation between an historic windows, with its properties and coordination system, and the wall where it is placed). The current system of classification used in the construction industry (CSI MasterFormat, Uniformat, OmniClass, UNI standards, etc.) will probably have to be extended to include these new criteria.

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[12] Maher & Rutherford, 1997.

[13] Arayici et al., 2006.

[14] Penttilä, 2007.

[15] Laakso & Kiviniemi, 2012.

The current research will attempt to facilitate this second point in particular. Without attempting to find solutions to all the problems raised, it seems evident that it would be useful to create a software “filter” that could manage the high level of detail of a BIM model while allowing the participants in the early stages of design to use simplified data in the decision-making process. Moreover, the research hypothesis is to use mathematical methods, and in particular Graph Theory, to drive this process.

1.3 Overview of the thesis

It is possible to schematically frame this research across three main categories: (i) building activity, building process and building heritage, (ii) knowledge representation in architecture design and (iii) new technology. Figure 2 shows a synopsis of the thesis.

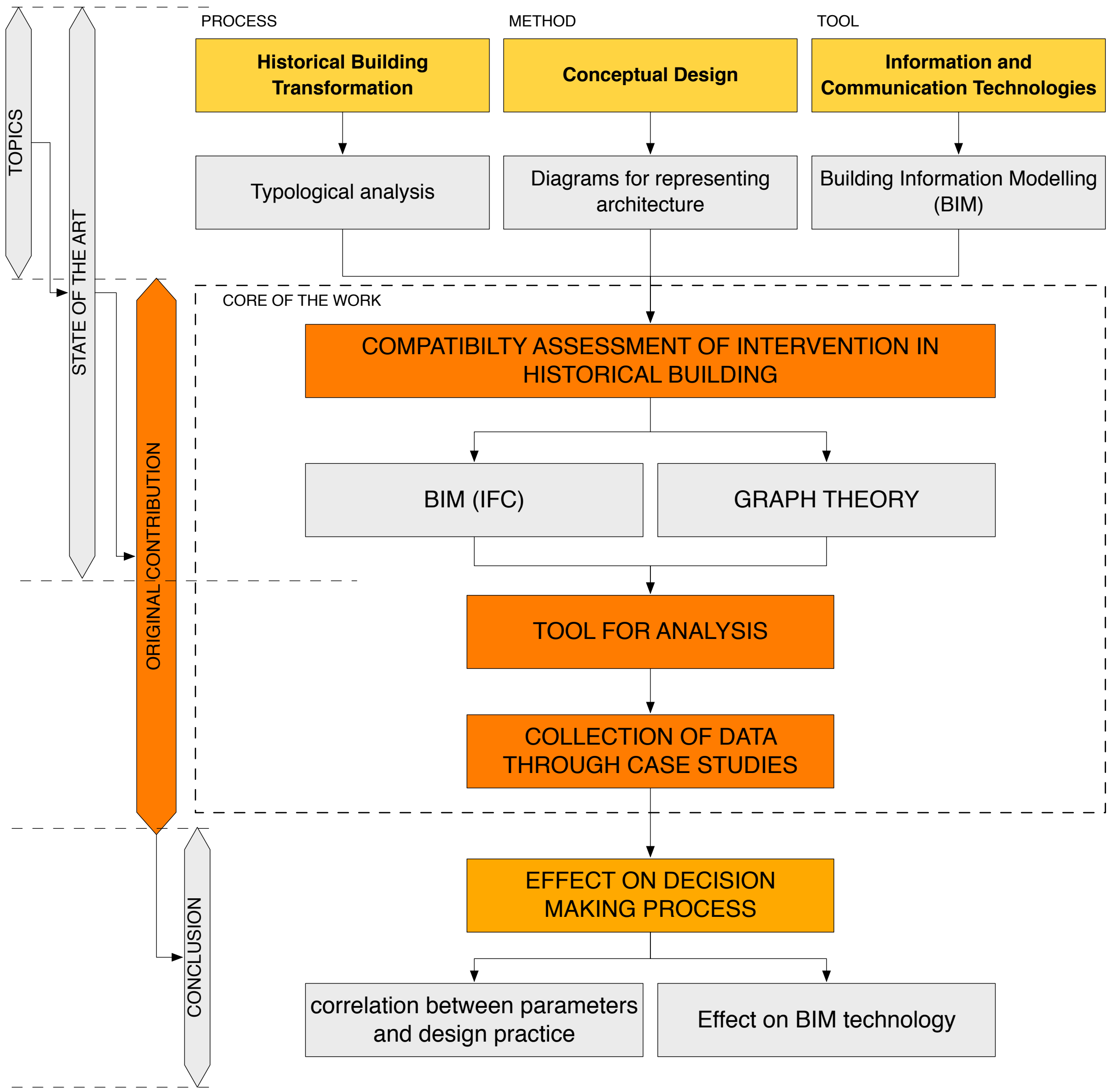


Figure 2 – Overall view of the thesis

Following a movement from the general to the specific, it is necessary to frame the present research in several connected backgrounds that are fundamental for understanding future developments. Figure 3 shows such a movement that reflects the correlation between the keywords related to the thesis.

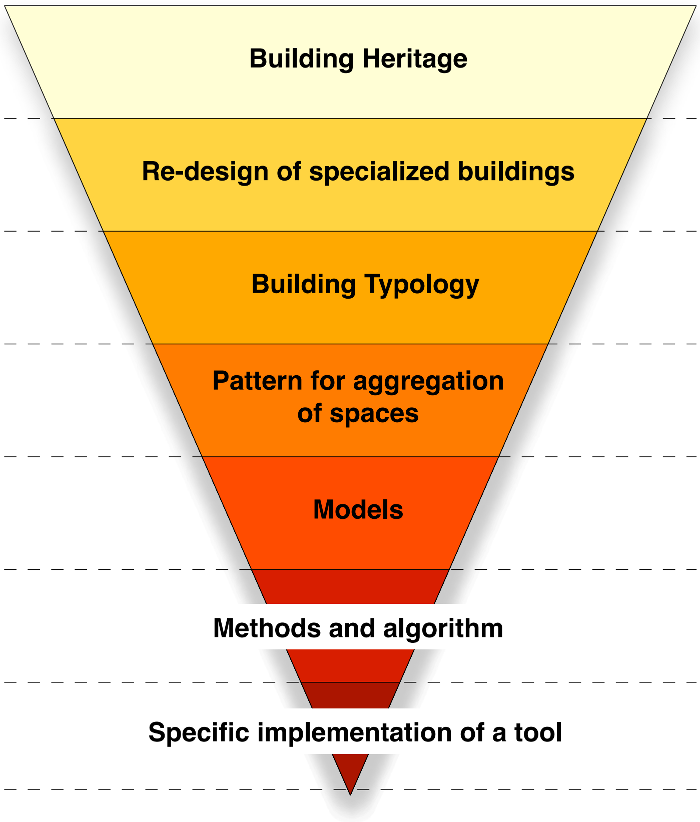
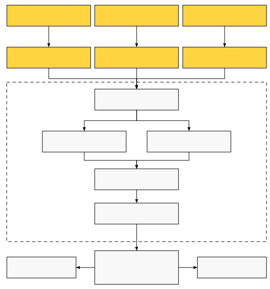


Figure 3 – Keyword correlation

2 State of the arts



In the context of architectural re-design, the designer does not act in a vacuum, but in the presence of a building body that is well-defined and uniquely characterized, in terms of its function and form. This body is the "counterpart" to which the designer has to constantly connect his imaginative activity and decisions. In many cases, the historical building is a source of inspiration: this is the "foreshadowing" (or "intention") project, which is always present in the designer's work, as part of the orientation and verification with which he inevitably confronts the constructed reality. This fact represents not only a limit, but also a possible creative trigger.[16]

The strong interconnection between the building and the historical city also implies that the designer will have to extend his scope to a large number of issues that extend beyond the building itself.

One such issue is related to the specific access to the building, with regard to the immediate urban surroundings and the building's relationship with the more general city infrastructure (the transport system, the main service infrastructure, etc.). Problems related to mobility, as well as the safety of users and operators, require a field of analysis and testing for all buildings. The formal characteristics of the existing architectural features, generally important in the case of specialized buildings, make it necessary for the designer to check the connections between the building and its urban environment, and they therefore demand particularly careful and qualified decisions about any changes to the historically established configuration.

In order to handle all these aspects it is necessary to study the problem from a multidisciplinary point of view. In fact, the investigation activity of the project presents a strong interdisciplinary character, assuming the distinctive features of "integrated design". The complexity of the functional layout and usability requirements of individual spaces necessitate the presence in the design team of a substantial number of specialists, including non-technical. The activities of the design team also imply a significant relationship with the world of industrial production of components and building systems. The need for integration between the disciplines that relate to the architectural design thus takes on considerable importance.

[16] Nuti, 2007.

For this reason, the analysis of the state of the arts addresses many topics, indicated in the icon above.[17] This chapter contains a discussion of the three topics which form the basis for defining the objective of this doctoral thesis. These are:

1) Historical Building Transformation, and in particular understanding of the constraints imposed by an approach based on the typological analysis;
2) Conceptual Design based on a graphical representation through diagrams;
3) Information and Communication Technologies, and in the specific case of BIM their applications in relation to the existing building.

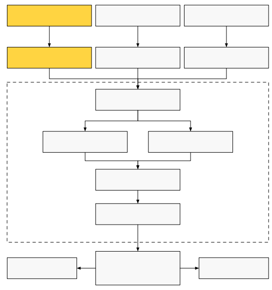
In the first section the main problems of the transformation of an existing building are outlined. Some methods for highlighting procedures to individuate factors in the evaluation of design compatibility will be described in further detail during the chapter.

The second section explains why diagrams and graphs are useful in the context of re-design and what benefits can be derived from the application of these methods.

The last section describes how BIM can be used for historical building heritage, highlighting the most important features of BIM in the context of renovations.

[17] The picture refers to the overview described on page 9.

2.1 Building transformations



"Transformation" and "Metamorphosis" are two key terms for exploring the process of creating architecture. They are almost synonymous, but in an article written in 2011 Portoghesi draws the following distinction:

While transformation describes a transitive action performed by a subject, metamorphosis seems to allude to a process that is autonomous or even endogenous. Architecture is continuously transformed by the efforts of those who design it and build it. However, it is also true, if we consider it as an expression of the society and culture of a specific time, we have to admit that, in its constant changing, it seems similar to a living organism that undergoes continuous metamorphoses. This is especially so if we take the biological meaning of the word, which usually refers to significant, showy transformations, such as for reptiles, or for caterpillars that become butterflies.[18]

The transformation of a building may reflect its **use** and its **form**. It may be radical, like a replacement, or limited, as in a restoration. It may be superficial or deep, lasting or fleeting, temporary or permanent. It may improve or worsen, it may raise or lower, expand or contract, and so on. Without question, it alters and sometimes erases the original building's very identity.

Particularly in Europe, the current condition of urban building heritage in this period of ongoing economic crisis makes **transformation** one of the few feasible ways to prevent the wastage of energy, time and resources and realize a sustainable intervention.

In recent decades, the industrial production system has changed radically, enabling a kind of virtuous transformation that is rarely planned on the urban scale. Some examples are related to the conversion of old industrial buildings into homes, offices, retail spaces, exhibition spaces or entertainment venues. In a few cases entire neighbourhoods have been "salvaged", repairing features that had increased consumption and compromised liveability, such as architectural barriers, poor safety and the lack of facilities needed for community life.

Renewal often means changing the intended use of a building, and after decades of trials has proven effective. It has often given rise to new creative dimensions through the treatment of architectural ills. In his famous book of 1977, *Form Follows Fiasco*, Peter Blake warned:

[18] Portoghesi, 2011, p. 34.

All over the world, buildings that have been recycled from an earlier function to a new one seem to serve their users better today than they ever did before – and better than contemporary, brand-new efforts designed and constructed to a form that supposedly follows and expresses its function. The best museums in Italy and in Spain, for example, tend to be recycled convents or palazzi of the Renaissance or of the Middle Age, whereas modern museums, designed specifically to display and celebrate the art of our century, look like cut-rate department stores with bargain basements up to the roofline. In Great Britain, the best concert hall may be a recycled brewery – now known as the Maltings at Snape in Suffolk; in Baltimore, the best art school may be a recycled railroad station – the Mount Royal Station, now become the Maryland Institute, College of Art; in New York, the best library may be a recycled courthouse – and the best theater may be a recycled library! In San Francisco, the nicest shopping center, Ghirardelli Square, is a recycled chocolate factory; in St. Louis, the beautiful headquarters of an educational laboratory was carved out of an abandoned Civil War hospital.[19]

We might wonder why such an effective treatment, despite the success of the best examples (Figure 4), has up until now been directed by the market instead of by conscious government strategy, and has been applied almost exclusively to abandoned industrial buildings.

Figure 4 – Auditorium Niccolò Paganini – Parma, Italy [20]

Therefore, it is necessary to extend efforts to determine the "code of conduct" or "behaviour" for interventions regarding historical buildings, enlarging the scope of investigations and considerations. These aim to identify a set of general criteria that

[19] Blake, 1977.

[20] The building was designed by Renzo Piano Building Workshop. Photo by Enrico Cano.

ensure the consistency of intervention with regard to the historical character of the architectural space.[21]

2.1.1 Causes of deterioration

Renovating an existing building perhaps represents a more complex design challenge, and certainly stimulates the development of new experiences and theoretical architectural approaches.[22] This in turn stimulates the professional to establish a set of constraints related to the pre-existing structure, and to engage in a process of respect for the historical fabric that does not exist with a new design process. However, after the early decisions have been made a number of problems arise related to choosing the most suitable type of intervention.

It is useful, before any design proposal, to understand the causes of the building's deterioration. These can be classified as shown in Table 1.

Table 1 – Causes of deterioration

Causes of deterioration	
1. Imminent danger or obsolescence	
1.1. Intrinsic causes	
	a. Geological reasons
	b. Quality of materials
	c. Errors in previous executions
1.2. Extrinsic causes	
	a. Unexpected events (earthquakes, wars, exceptional weather conditions, volcanic activity, etc.)
	b. Extended events (degrading agents, wind, thermal cycles, vegetation, rainfall, marine aerosols, etc.)
	c. Direct anthropic actions (wear and tear, fire, vandalism, theft, etc.)
	d. Indirect anthropic actions (abandonment, lack of maintenance, improper use of the premises, inappropriate interventions, pollution, traffic, etc.)
2. Economic reasons	
	a. Development of public plans
	b. Spontaneous private action

[21] Nuti, 2010, p. 165.

[22] Vivio, 1997.

In particular, when the building has a high historical value, the design must respect many factors and assume a configuration that does not endanger the cultural significance of the building. Many researchers have studied specific methodologies for interventions regarding existing buildings. These will be described in the following sections.

2.1.2 Possibilities of interventions

"Possibilities of interventions" does not mean classifying the type of intervention (or in this context recalling the contents of the categories under which the current legislation classifies "actions on buildings", from restoration to maintenance). Instead, the intention is to highlight the typical requirements of some operating modes associated with the phases of design and construction.

The intervention may involve actions which relate to (1) the fruition of the entire building or (2) local action on adaptation, consolidation, repair and replacement of structural components to ensure a certain level of functionality.

Within the first category, two methods can be highlighted: (1a) a substantial modification of the structural and functional organization of the pre-existence, or (1b) the relation between new and old can be expressed by simple juxtaposition, without any interaction between new compartments and old structures. The insertion of elements, consisting of tiers and/or volumes, represents the most evident intervention included in method 1a.

These can usually be expressed by the actions of (i) "**subtraction**", (ii) "**addition**" and (iii) "**transformation**", applied to a well-defined pre-existing architectural structure or a homogeneous class of organisms. A brief summary of the method of design described by Nuti follows.[23]

The first mode, (i) subtraction, refers to a complex architectural structure, enriched or contaminated with respect to the original typological system over the course of history through a series of additional interventions or processes. The building is the result of a sedimentation of differently characterized elements. In many cases the operation of "subtraction" coincides with the discovery of the original typological system, and highlights its most significant transformations. This process of discovery is based on a careful reconstruction of the process that understands its causes and effects.

Action (ii), addition, implies a deep understanding of the original typological process that created the architectural structure. In fact, the new architectural elements have to create a form of equilibrium with the existing building. In this equilibrium the added

[23] Nuti, 2007, p. 47–49.

elements often play a strategic role in relation to the configuration of the project. The addition of new architectural elements inside or outside an existing organism may also be structured in different ways:

- Insertion of architectural elements to maintain the legibility of the original space or, conversely, interact more or less strongly with the existing building;
- Insertion of architectural elements with strong formal recognition within or outside the existing buildings, usually lifts, stair-blocks, plant blocks;
- Addition of new volumes to new destinations according to functional criteria of formal “similarity” or “dissonance” to the pre-existing building.

Action (iii), transformation, implies a substantial change to the geometric-dimensional position and performance of the existing architecture in order to define a new overall configuration in which the interventions are integrated with the existing spaces.[24] Transformation in general means changing spaces and relationships, as well as systems of access and movement. The role of the designer during the proposal to transform an existing building is certainly more challenging in this phase than for the processes of subtraction or addition.

The possibilities of transformation, due to its nature, are diverse. We might mention the following: (a) the process of fragmentation of the spatial units aggregated in plan and in elevation of repetitive entities,[25] (b) interventions in the hierarchical order that regulate the aggregation of serial spaces and (c) the use of innovative sequences of fruition and perception regarding the original typological organization (the modification or creation of new sets of access systems and internal mobility, variously arranged in plan and height, may offer new ways of reading the internal space of the building).[26]

The three modes of subtraction, addition and transformation described above interact significantly with the consolidated criteria for the “**recognition**” (readability) and “**reversibility**” of restoration building, in acting as characters that identify the pre-existing building. The methodological framework of reference for planning and construction may then expand and specify further, beyond this basic contribution. Although this framework is derived from a logical and coherent systematization of the existing problems, it will in no way generate a set of strict design rules in which to entrust our action across different contexts: the role and responsibility of the designer cannot be reduced to a sort of unitary normative.

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[24] Nuti, 2010.

[25] Boaga, 1995.

[26] Di Battista et al., 1995.

2.1.3 Approaching historical buildings

Stratifications built over initial configurations recur throughout the history of architecture. In some cases the design respects the old design, but in others a tampering with the layout due to a change in needs may be easily seen. We need only consider the intervention of Filippo Brunelleschi on the gothic Santa Maria del Fiore in the fifteenth century, or the *"compromise solution that Alberti was almost forced to adopt"*[27] in the Temple Malatesta of Rimini (1449–61) *"from the moment he decided to apply a classical system to a system of non-classical building"*.[28]

In the contemporary age, architectonic production perhaps seems released from deep theoretical research. However, most academics and researchers agree on the need to create a dialogue between a city's cultural history and its future transformation through architectural or urban projects. In a recent essay Gianfranco Spagnesi offers some ideas for recognizing a series of relations between operating modes and historical criteria, considering the changing attitudes to architectural evidence in every age. He also explains the relation between design and history; however, this last is increasingly often set aside in favour of economic factors.[29]

The reuse of past architecture is not necessarily connected to its functional or physical obsolescence, but may be related to superficial aspects: sometimes to a simple change of ownership, from private to public; or, as was more of an issue in the past, a change of faith or governance. War events have also influenced decisions to maintain, restore or replace entire buildings. Identifying the type of intervention on pre-existing buildings can be hypostasized by studying a population of cases and identifying the differences in recurrent approaches.[30]

We have to refer mainly to two international agreements for the protection of building heritage, especially when the building has a high historical and monumental value.

If we consider the Athens Charter of 1931, especially article II, then *"When, as the result of decay or destruction, restoration appears to be indispensable, it recommends that the historic and artistic work of the past should be respected, without excluding the style of any given period. The Conference recommends that the occupation of buildings,*

[27] Wittkower, 1994.

[28] Idem.

[29] Spagnesi, 2005, p. 27.

[30] Vivio, 1997, p. 219.

which ensures the continuity of their life, should be maintained but that they should be used for a purpose which respects their historic or artistic character".[31]

Moreover, it is possible to extract further information from the Venice Charter of 1964, article 9 of which states that the *"aim is to preserve and reveal the aesthetic and historic value of the monument […]. It must stop at the point where conjecture begins, and in this case moreover any extra work that is indispensable must be distinct from the architectural composition and must bear a contemporary stamp. The restoration in any case must be preceded and followed by an archaeological and historical study of the monument*".[32]

These Charters are guidelines for historical and monumental building heritage. However, the final design depends greatly on the decision of the owner, who will decide to maintain or radically change the original function, and the designer, who will elaborate a solution.

Another approach, more objective in this sense, consists of formulating general rules based on the identification of the typological factors of the historical building. The methods and procedures usually adopted in the analysis of an existing building give the designer a series of facts relating to the genesis of the building type under investigation and its subsequent amendments.

The pre-existing building is the result of a usually detailed and complex story, involving a series of transformations with respect to its original typology, whose characteristic features must still be identified. The detection of "building pathologies", related to both function and/or technology, must be placed within a highly structured knowledge framework. The construction of this framework constitutes a series of "design rules" through the recognition of historical-typological features that, over the centuries (and for buildings that have been intentionally specialized), have been adopted for the project and for the construction of a particular architectural organism.[33]

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[31] ICOMOS, 2011.

[32] Dezzi Bardeschi, 2003, p. 400.

[33] Nuti, 2010.

2.1.4 Typological assessment of specialized buildings

The typological assessment may be one possible method for overcoming the "subjectivity of design" in a project, providing important direction during the design process. The designer can read and interpret the typological factors to develop a intervention that is compatible with the urban fabric, preserving the historical memory of the place.

This method is well documented through the studies conducted by Professor Muratori of a peculiar building type: that is, the serial historic building.[34] Especially in Italy, a school of architectural thought has gained strength since the '70s that highlights the invariant through specific methods of studying a pre-existing building within a particular geographical and historical context (an example of a patterns study for residential aggregation is given in Figure 5).

[34] In the context of numerous studies on the genesis and transformation of building types, for both basic and specialized buildings, in addition to those of the founder of this line of research, Saverio Muratori (Studies for an active urban history of Venice, 1959), we recall: G. Caniggia e G.L. Maffei (Architectural composition of building typology, 1979; The project on the basic buildings, 1984); G. Caniggia (The rules possible, 1987); L. Macci e G. Villa (Notes for a methodology of analysis for urban sections within the historical city centre, 1989). Original titles are in Italian.

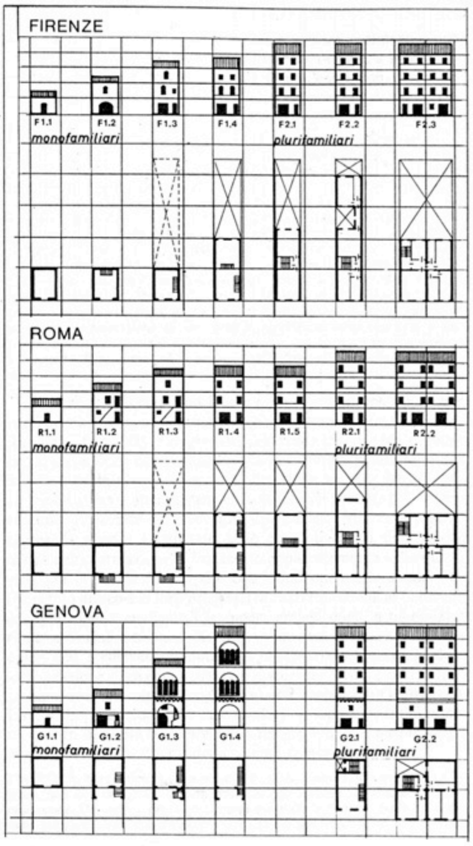

Figure 5 – Pattern of the main mutations of residential buildings[35]

Figure 5 depicts recurrent schemes that are easily detectable by observing the urban fabric. The study is conducted by showing the invariant factors in relation to structural axes, number of tiers, aggregative mode of spaces and function for common historical houses. Many other studies build on this foundation, such as those by Giannini for Genoa, Caniggia for Como, Maffei for Florence, Maretto for Venice, Cervellati for Bologna, Bollati for villages in Calabria, Vaccaro in Tuscany, and so on. Their younger followers have studied dozens of minor centres.

In contrast to the typological study of residential buildings, specialized buildings (hospitals, theatres, commercial or educational buildings, etc.) have a higher functional complexity that is manifest through a more articulated architectural layout. Often this layout obeys the precise principles of rigorously planned activities, hierarchically organized.

In general, there are two main patterns of aggregation for elementary functional units: **polar** and **serial**. Examples of the serial type are present in office, residential, educational, health, tourist accommodation and administrative buildings; examples of the

[35] The Roman environment is composed of a patchwork of anonymous small houses, accumulated over the centuries, from the reconstructions that the city has had since the Renaissance through to examples of baroque architecture. The overall work is almost all the result of almost modest and unknown masters, rich in shapes, and varied in detail and ingenious solutions (Caniggia & Maffei, 2008).

polar type include buildings for exhibitions, retail, sports and so on. This division has a purely indicative value as it is possible that some uses present both types of organization in the functional core.[36]

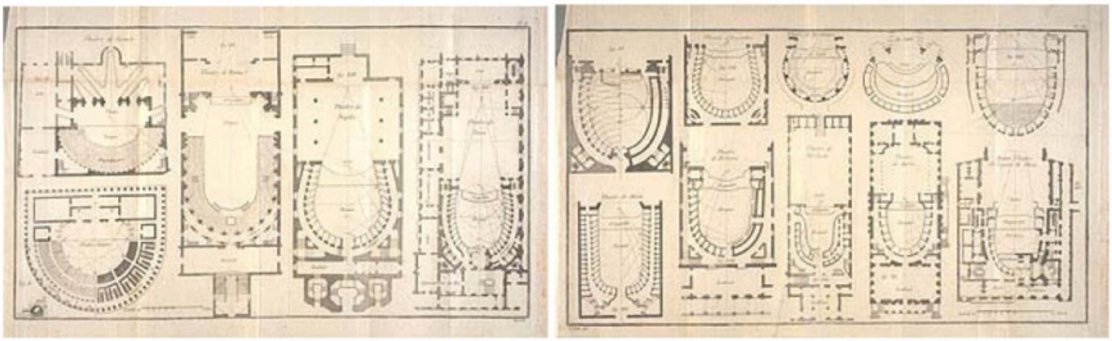

Figure 6 – Specialized building types: the evolution of theatres over time[37]

The correspondence of the laws of aggregation and decomposition of the spaces about the new features, with those deduced from reading the pre-existing building, is the first indicator of a correct start to the evaluation process of convertibility.

The hierarchical organization of space is one of the features that can be detected in many specialized buildings. For instance, the presence of a central axial position, the symmetry of the layout configuration, recurring localization of certain functional areas within the building, and structuring of internal mobility (subdivision of paths into primary and secondary routes) are some of the elements that can match a pre-existing building (to a greater or lesser extent) to a certain use.

The re-design of specialized buildings thus assumes as its first step a historical-critical reconstruction of the original layout, and a comparison with that implied by the new uses that are to be put in place.[38]

2.1.5 Methods for evaluating quality for a re-design project

Many academics assert that it is necessary, before proposing a design solution, to reflect on the pre-conditions and the internal consistency of the scientific re-design operations, in order to understand the interrelationships that link the techniques/technology to the design/typology of an existing building. In particular, the methods of historical-critical analysis resulted in the birth of a concept of architecture as a product of material culture, surpassing its exclusively formalistic powers. In such an

[36] For instance, office buildings can be organized as singular or double linear aggregative schemes of consecutive functions or adopt a solution as open-spaces.

[37] Pierre Patte “An essay on the architecture of theatres”, 1782.

[38] Nuti, 2007.

approach it is essential to identify the **evolutionary mechanisms** inherited from the historical process, in order to define what is the real potential of a pre-existing building in terms of its resource usage, so as to give rise to a congruent hypothesis of transformation.

One possible method[39] is based on defining a precise procedural focus on the comparison between the “pre-existing building” and the “proposal of a new design”. The method is subdivided into five key stages:

1. **Reading of morphological type**, through an explanation of the qualitative factors that characterize the building type;
2. **Establishment of new uses**, to be checked through the needs emerging from social, cultural and economic development;
3. **Identification of a distributive compatible model of uses**, the design configurations of the general model, highlighting in particular seriality, polarity, hierarchy, usability;
4. **Formulation of rules of transformation**, rules for controlling the sustainable intervention, which have to be respected in order to achieve a correct design solution;
5. **Assessment of compatibility**.

[39] This method is well documented in the literature, especially by national researchers. In particular it is possible to find references in: Di Battista et al., 1989; Nuti, 1991; Biagini, 2007.

Reading of morphological type (1)

The first stage of the method involves recognizing the rules of aggregation that, through successive adaptations, have shaped the existing building. A reading of the pre-existing building shows the positional and dimensional geometric rules that organize its functional spaces, and which shape the static-constructive, stylistic and formal structure of its exterior. This is done by establishing and comparing grids that are designed to highlight the invariable functional, structural and formal aspects of the building.[40]

The first points were essentially connected with the phase of studying the pre-existing building, becoming more familiar with its fabric and identifying its invariant elements. A more extensive and comprehensive framework is that described by Nuti and Campolongo, [41] which classifies the qualitative factors across four homogenous categories:

A. Environmental and urban factors;

B. Dimensional, distributive and functional factors;

C. Technical and technological factors;

D. Formal factors.

Each of these categories also has sub-factors, as shown in Table 2.

Table 2 – Classification of the evaluative factors

A	B	C	D
Climate	Organization of SU	Material and compounds	Articulation solids and voids
Natural pre-existence	Aggregation of SU in FU	CT for structure	Ratio structure/envelope
Soil morphology	Aggregation of FU in Building	CT for external facade	Volumetric composition
Urban standards	Internal circulation	CT for internal subdivision	Material and surfaces
Functional organization	External accessibility	CT for plants	Decorative elements
Accessibility		CT for surfaces finishing	
Volumetric features			
Pre-existing features			
Definitions: SU = space unit – FU = functional unit - CT = construction techniques			

This is based on a qualitative approach where each sub-category refers to a specific built issue. Although each of these factors can be studied and considered independently, they have a strong interrelation and some of them can significantly influence the evaluation of the other. The evaluation has to be reported and analysed: these materials must be collected as documentation and interoperate for a new re-design proposal.

[40] Biagini, 2007, p. 53.

[41] Nuti & Campolongo, 1989, p. 11–24.

If we look in detail at Table 2, we can explain the meaning of all the categories in more detail. The first category (A) is based on the analysis of the relationship between building and urban context, in particular highlighting the factors regarding the environmental and climatic aspects in function of the types of aggregations. The analysis continues by identifying those typological models that can be subdivided in accordance with recurrent geometrical rules based on dimensional recurrent schemes, urban accessibility and mobility to the area, and types of environments and their combinations. The second category (B) addresses the characteristic of internal space. Moving from the generic to the particular, it is possible to highlight the knowledge of the original condition of the distributive layout and the several historic transformations that the building underwent. The analysis continues with the identification of the original pattern (the base type module for aggregative spaces). This process allows the identification of a series of invariant schemes that apply to a homogeneous family of buildings. The third category (C) refers to material characteristics and construction techniques regarding the load bearing structure, external envelope, internal and external partitions, plants and systems of protections. The last category (D) makes reference to an architectural scale. With this activity the aim is to achieve a complete description of certain architectural linguistic codes detectable from groups of homogeneous buildings, the object of the new re-design.

Establishment of new use (2)

The evaluative phase of the design proposal (which may be performed graphically or analytically) instead requires a conceptual design phase in which the proposal is matched with a specific programme. This must therefore be compatible with the laws and regulations specific to the relevant country. It is essential to select from the various technical standards in the construction field those aspects that most directly affect the degree of compatibility of a certain hypothesis regarding the reutilization of the pre-existing building in relation to its intended use.

The formulation of alternative usage patterns, which implies the statement of requirements relating to the activities that may take place within the spaces under consideration, is possible only through a qualitative (needs–requirements–performance) regulatory approach. This approach is particularly relevant to enabling an effective control of quality, especially for the design of the environmental system.

Identification of a distributive compatible model of uses (3)

Defining a new function for a specialized building must respect the typological rules and involve a study of the capability for transformation. The concept of “transformation” can be understood as the capability for mutating the use of the historically established architectural spaces, with respect for the typological features of the pre-existing building.[42]

In general the principle of respect for the typological system within a transformation proposal is easily shareable among many professionals. The difficulties for the designer are identifying what are the **qualifying characters** (from the typological point of view) of the architectural organism; that is, those characters that cannot be changed. Recognizing these is necessary but not sufficient for the renovation, however, as this recognition tends to act as an unsurpassable “limit” for the designer. The phase of “reading” an existing building must go beyond the logic of limits and boundaries, to allow for the determination of the original configuration and all the different successive transformations.

The new design has to work in dialogue with this historical concatenation of the building’s characteristics. Concepts of “seriality”, “polarity” and “hierarchical organization” of the constitutive spaces of the pre-existing building are the first reference for understanding the building’s logic of aggregation. We may add and integrate dimensional, geometrical, material, static and constructive factors, as well as many others, through which it will be possible to conduct a series of analyses of potential compatibilities. Well-established procedures allow the requirements of accessibility, mobility, feasibility, environmental comfort, ease of equipping or furnishing, security, and so on to be checked.

Regarding the new functions to be associated with a pre-existing space, it is helpful to consider these as flexibly as possible through a schematic structured design. The demands of rigorous requirements that match a new use to a pre-existing architectural space have often led to forced and irreversible failures in the design and implementation of recovery interventions.[43]

The quality of historical architectural spaces is generally very high, not only in terms of technical-constructive features, but also in terms of their inherent flexibility with respect to variable uses over time. The individuation of a new function must refer to a group of homogeneous functional possibilities of association, avoiding a rigorous approach to textbook procedures that will make the design process too constrained and rigid. It is always worth considering that absolute "efficiency" will never be reached for any design and construction action, and that the best results are obtained in a given context and within well-specified boundary conditions.

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[42] Biagini, 2007, p. 44.

[43] Nuti, 2007.

Special consideration should be given to the legal compliance of historical buildings, both from the functional and structural point of view (in particular with respect to the seismic requirements) and the so-called "security plan" (which includes many different aspects, from the elimination of architectural barriers to the working conditions of employees, fire safety, etc.).

Notwithstanding this, it should be asked whether such public specialized buildings meet these provisions, and we emphasize the need for a more flexible design approach that is made for today's legal environment. The priority is always to preserve the particular quality of the spaces of an architectural structure and its overall configuration, avoiding irreversibly compromising interventions through an uncritical application of the law.

The search for alternative technical solutions to those usually applied through the identification of "equivalent performance conditions" is an extremely helpful and inspiring area in which interdisciplinary concepts and practice in the field of architecture are reactivated.

Formulation of rules of transformation (4)

This type of evaluation has to follow specific "rules of transformation". Formulating these rules is the most delicate phase of the whole process of evaluation, because it is through them that the design constraints are decided and the building will assume a particular configuration. According to Biagini[44] these rules can be grouped into two broad categories:

- Rules **with a significant alteration** of the spatial organization (Rules A);
- Rules **without a significant alteration** of the spatial organization (Rules B).

Following this division we can identify two substantially different approaches for the transformation: Rules A, the obsolescence of types, mainly in specialist construction, requires a reinterpretation of the semantic values of the pre-existing building, and a review of the total space; for Rules B, the definition of new uses goes through a substantial confirmation of the typological characteristics of the pre-existing building.

The sub-rules of set A are:[45]

A1. Addition of new parts of the building that are structurally and functionally independent with respect to the existing building;

[44] Biagini, 2007, p. 58.

[45] For the first set of Rules A, we may respect the rules of this category by also including the rules defined for B. Thus, set A is a set that also includes B.

A2. Insertion of new connections between the chief internal path and the new volumes and/or urban space;

A3. Inclusion of differentiated spaces in size and height, within rooms of large size;

A4. Volumetric subtraction;

A5. Interaction between old and new formal languages.

On the other hand, set B consists of:

B1. Surface controls useful in relation to the useful depth and height of the rooms;

B2. Redefinition of internal and external mobility and accessibility systems;

B3. Insertion and/or removal of structural grids;

B4. Redefinition of the external envelope, particularly the shell, in order to get the best internal conditions of environmental comfort;

B5. Redefinition of the mode of perception/introspection.

In the last example issues of architectural composition to do with aspects of consonance or dissonance of formal languages between the pre-existing building and the new construction emerge more clearly, as does a final analysis of tradition versus innovation that opens up an investigation of the infinite possibilities of compositional and technological experimentation.

(4) Assessment of compatibility

According to Nuti,[46] it is possible to highlight methods and procedures for the comparison and evaluation of a design solution along two main modes, both theoretically and operationally.

The first method, which we have defined as “analytical”, is based on the detection of lists of requirements relating to homogeneous factors that are the object of our investigation. The evaluation is performed by comparing these two values: the first represents the value of the pre-existence, and the other the value of the design solution.

The second method, called “graphic”, proposes a series of direct analyses of building objects and tends to highlight, in a very simple and direct way (through a drawing) a set of geometric features regarding the functional organization of the distribution of buildings and the constructive systems used each time.

[46] Nuti, 2010, p. 175.

2.1.6 Italian standards and references for the renovation process

In the wider environment of building recovery, it can easily be seen nowadays that the technical culture for identifying degradation and the modalities for solving different cases are broad and segmented. However, especially under Italian legislation, there is a set of rules that allows us to identify a method for confronting the design process. Figure 7 shows the framework of the Italian standard regarding the building process and the definition of the steps of renovation of existing buildings. The chart reported below is cited in and translated from UNI 11151 (ITA) – Building process – Definition of the steps of renovation of existing buildings.

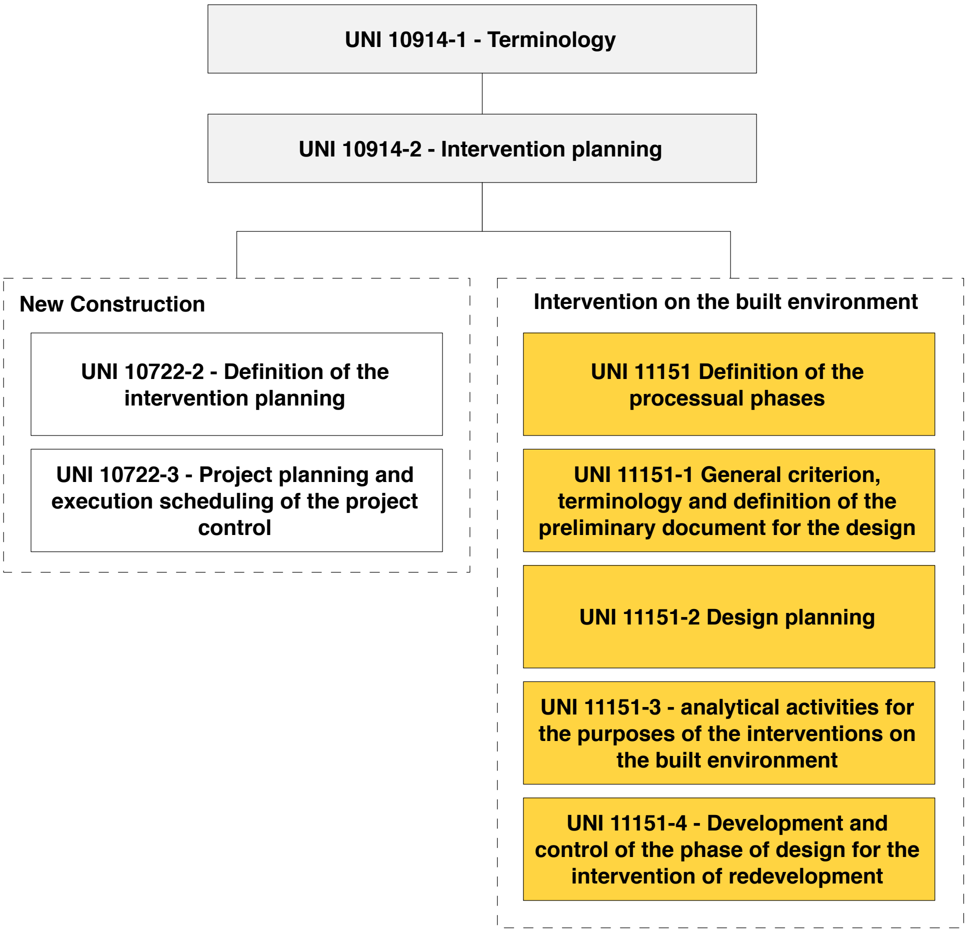


Figure 7 – Overview of the UNI standards

UNI 10914-1 is an Italian standard related to the definition of terminology, while UNI 10914-2 presents the planning of an intervention. After these two introductory standards we have two main branches separated into new construction and intervention on an existing building.

Although the two processes could look similar, in our opinion it is necessary to clearly separate them into specific categories. In the first paragraph of the Methodology the integration of this standard has been proposed, with an implementation regarding the use of BIM.

If we compare processes of design, as shown in UNI 11150, we can see that the flowchart describing the process for an existing building is substantially different from any process related to new construction.

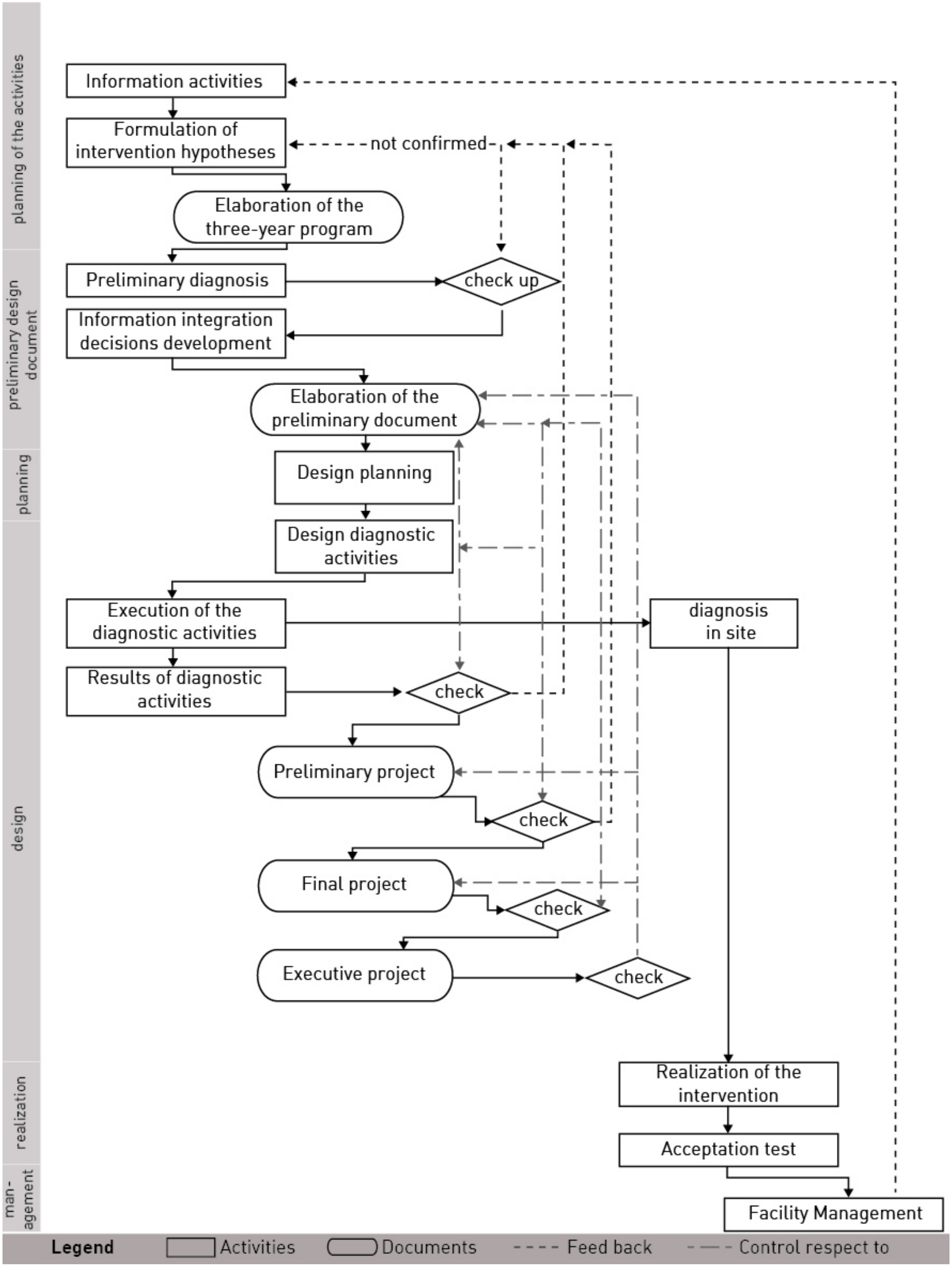


Figure 8 – Sequences, relations and constraints of the intervention phases on an existing building

As shown in Figure 8,[47] the flowchart is subdivided into six macro phases: (1) planning of activities, (2) preliminary design document, (3) planning, (4) design, (5) realization and (6) management. In each of these macro groups, there are activities and documents that are specific for each phase.

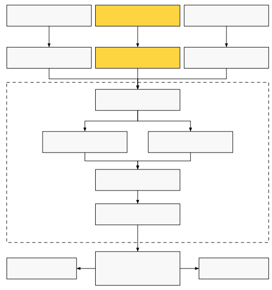
The UNI 11150 starts with an initial proposal of “hypothesis of intervention”. According to the theory discussed above, this phase should occur after a specific diagnosis that allows for the identification of several typological factors.

In our opinion, another point on which the flowchart should be revised is the relationship between the phases of “design” and “realization”. During the redevelopment of historical buildings, it is often possible to have a complete knowledge framework about the building only after the first preliminary demolitions. In that sense, we would highlight a missing loop that includes the phases of diagnosis, design and realization in a common space.

Although the diagram is complex and full of information, in the course of the thesis we will focus on the preliminary diagnosis phase as linked to the decision-making process. Moreover, we will show some proposed changes to the building process, especially where the process has to accommodate the BIM.

[47] The original document has been translated into English directly from the Italian.

2.2 Conceptual design



Design is a *"search for the most appropriate effects that can be obtained in a unique context"*.[48] This quotation by John Archea summarizes in a very few words the meaning of design. Moreover, we can argue that this search is *"an activity aimed at achieving certain desired goals without undesired side- and after- effects"*.[49]

According to Kalay, design can be considered a problem-solving activity and *"the problem it sets out to solve arises from the inability of a current situation to satisfy some needs"*. He continues by proposing a series of questions about "*how can we tell if a proposed design solution will achieve them? How can we measure the "goodness" and uncover its undesired side and after-effects before constructing the buildings? How can we begin the search for design solutions in the first place?"*[50]

An answer can be found in the study of the history of architecture: in particular, research into "best practice in design" has perplexed philosophers and architects since Ancient Greece. In the first century BC, Vitruvius offered some answers to this question, providing a good solution through specific geometrical proportion. Since then, architects and researchers have tried to formulate theories, methods and tools that will help the designer to "predict" the results.

In the recent era, the process of architectural design can be explained as a form of problem solving that ensures the designer meets the design goal and reduces any possible errors. This process, which has been practised for hundred of years, was formalized for the first time in the '60s and is represented by four main phases: analysis, synthesis, evaluation and communications.[51]

The starting point for many design methods has been the notion that design is a process of searching for a solution that satisfies a given set of goals and constraints. In the literature many methods of design can be found: search methods, constraint satisfaction, ruled-based design, case-based design, among others.[52]

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[48] Archea, 1987.

[49] Rittel & Webber, 1973.

[50] Kalay, 2004 p. 205.

[51] Edwards, 1979.

[52] The search method is based on the production of a candidate solution and the selection of the "right" solution for further development. Often the method is subjective and has to comply with some requirements. Constraint satisfaction is a method that makes it possible to look for a direct solution to the problem, instead of searching through the solution space of a problem. Ruled-based design we can consider the continuation of the classical method elaborated by Vitruvio and described in "De Architectura".

Regardless of the method used to achieve the design goal, one of the key elements in the success of the design is a focus on communicative issues such as coordination among the participants in the design process. In a communication process, before the "message" is transferred we must define a system of "encoding" that fits the medium of transmission. After that the receiver, using a previously established language or code, is able to decode the message and understand the message and its meaning.

The main mechanism that transforms a reality or an idea into a communicable message is **abstraction**. *"Abstraction extracts and distils the meaning of the message, focusing attention on its salient characteristics. Which details are preserved, and which ones are omitted, depend on the subject of communication, on its purpose, on the knowledge of the receiver, on the connect of the commutation, and on the medium used for its transmission*".[53]

For example, if we consider the second floor plan of the Gropius House shown in the figure below, it is possible to represent the same floor plan with two different types of encoding, as depicted in Figure 9.

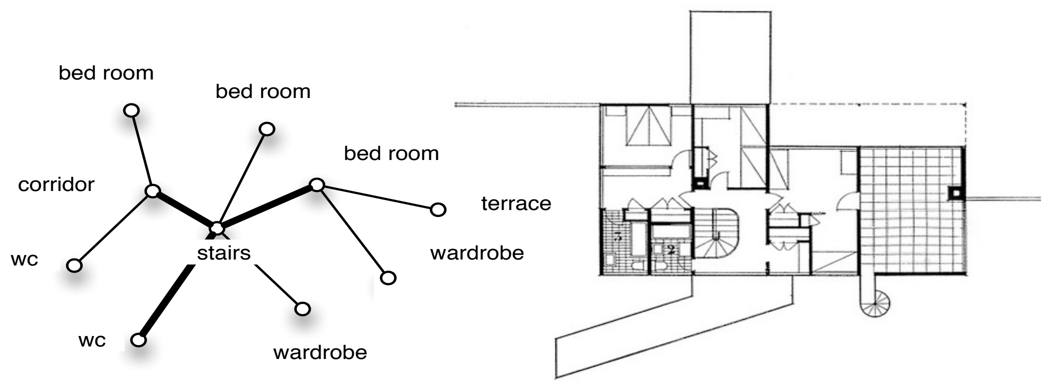

Figure 9 – Two different abstractions of the same floor plan

A high degree of abstraction therefore makes communication more efficient, though not necessarily more effective. Abstraction can help to draw certain specific features to the receiver's attention. Clearly the balance between abstraction and the loss of information has to be decided in accordance with the knowledge of the receiver, because this form of representation leaves out a lot of information that must be completed by the receiver.

[53] Kalay, 2004, p. 88.

2.2.1 Looking at architecture through diagrams

The relationship between diagrams and architecture is well documented in the work of Hellen Do and Nigel Gross. They argue that *"diagrams are essential representations for thinking, problem solving, and communication in the design disciplines, in particular those concerned with making physical form: mechanical and civil engineering, graphic design, and architecture and physical planning."*[54]

Drawings, diagrams and sketches are the most basic forms of representation; they are the medium of transport from concept to material. They can also represent relationships, forces and flow rather than just three-dimensional elements and aesthetic vision.

According to Do and Gross: *"in the early phases of designing, architects draw diagrams and sketches to develop, explore, and communicate ideas and solutions. Design drawing, an iterative and interactive act, involves recording ideas, recognizing functions, and finding new forms and adapting them into the design."*[55]

Drawings are not only a vehicle for communicating ideas but also a tool for the designer to manipulate and understand the forms they are working with.[56]

Architectural diagrams, for instance, employ a full range of graphical indicators, including topology, shape, size, position and direction, whereas diagrams in other domains typically employ only one or two of these characteristics. For example, electronic circuit diagrams use only shape and topology to convey the identity and connections of components; the position, direction and size of the graphic symbols are irrelevant to the meaning of the diagram.

In architectural diagrams abstract signs represent physical elements and spatial relations. The symbols used to represent elements (walls, doors, rooms, etc.) in an architectural diagram are not generic or arbitrary and their shapes and sizes derive from particular considerations.

In light of the continuum of graphical representations used in architectural design, it is useful to describe the differences between a diagram and a freehand sketch.

A diagram is an abstract form of representation for a concept, composed of symbols. Its elements and spatial relations can be expressed as a set of statements. It explores, explains, demonstrates or clarifies relationships among parts of a whole, or it illustrates how something works (a sequence of events, movement or a process).

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[54] Do & Gross, 2001, p. 1.

[55] Idem, p. 3.

[56] Edwards, 1979.

A sketch, however, represents attributes of form and shape. *“A sketch often comprises repetitive overtraded lines made to explore precise shape, rather than the intentionally abstract shapes of a diagram, and it uses graphic modifiers such as tone and hatching to convey additional information”*.[57]

2.2.2 An overview of the use of diagrams for designing

The use of diagrams and schematic representation is well documented in the history of architecture[58] and it is possible to draw a sort of parallel with the birth of functionalism and the Bauhaus.

At that time, all the research on compositions of building types converged into a result of general value. In 1928 the work of Klein on the criteria of layout compositions was published for the first time (see Figure 10, from *Neues Verfahren zur Untersuchung von Kleinwohnungsgrundrissen*, in Städtebau, 1928, p. 16).

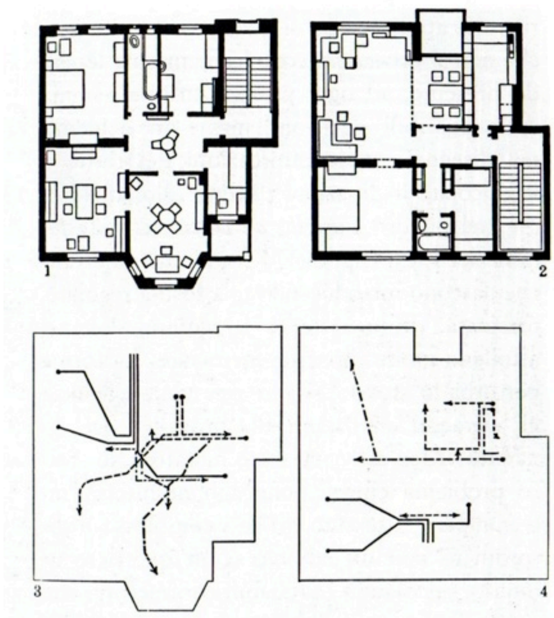

Figure 10 – A. Klein – distributive studies

The lectures of Walter Gropius were also based on the transmission of simple but fundamental concepts concerning the activities of the inhabitants. For instance, he elaborated forms of quality for light and ventilation based on the ratio between height and distances between blocks of buildings (Figure 11).

[57] Do & Gross, 2001, p. 4.

[58] Benevolo, 2002.

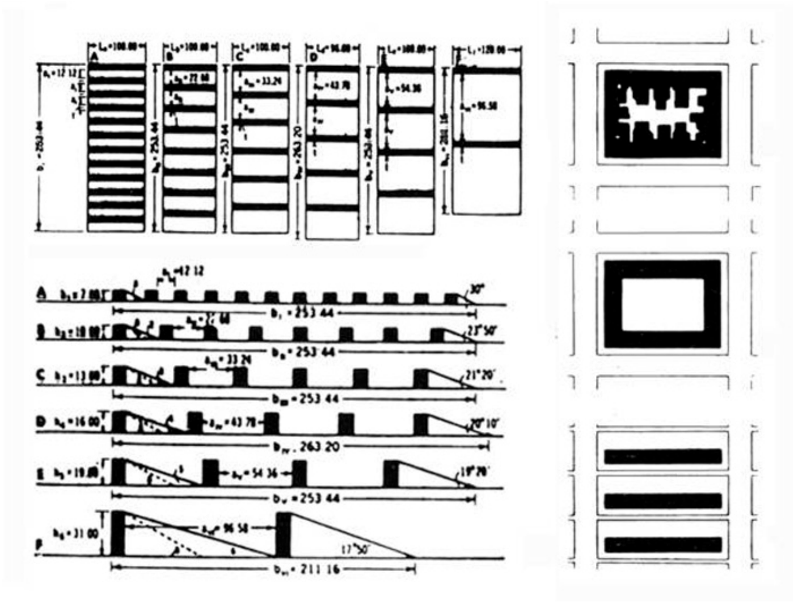

Figure 11 – W. Gropius – Density diagrams

Moreover, interesting examples and studies can be found across Europe from the same period of history. For instance, the diagrams in Figure 12 are taken from a work by B.J. Harrison, H.D. Whitney and C. Woodard published in *The Architectural Forum* in 1936.

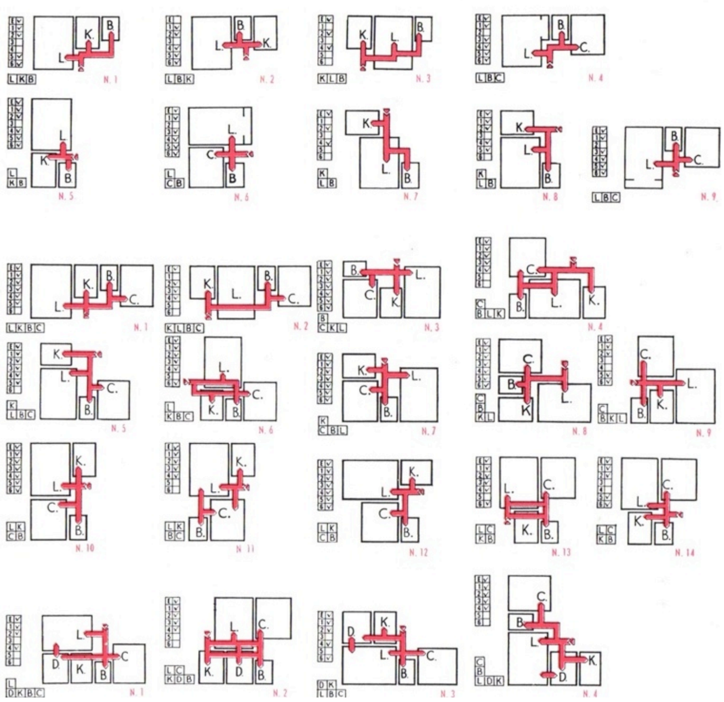

Figure 12 – B.J. Harrison et al. – Distributive scheme[59]

[59] Carbonara, 1976, p. 90.

In Italy a similar approach was taken by the studies of the Italian rationalist movement. In 1933 Giuseppe Vaccaro elaborated a diagrammatic model for architecture while designing the Faculty of Engineering in Bologna.[60] In his work, he represented spaces and relationships between them using language taken from electronic circuitry rather than pure architectural drawings (Figure 13).

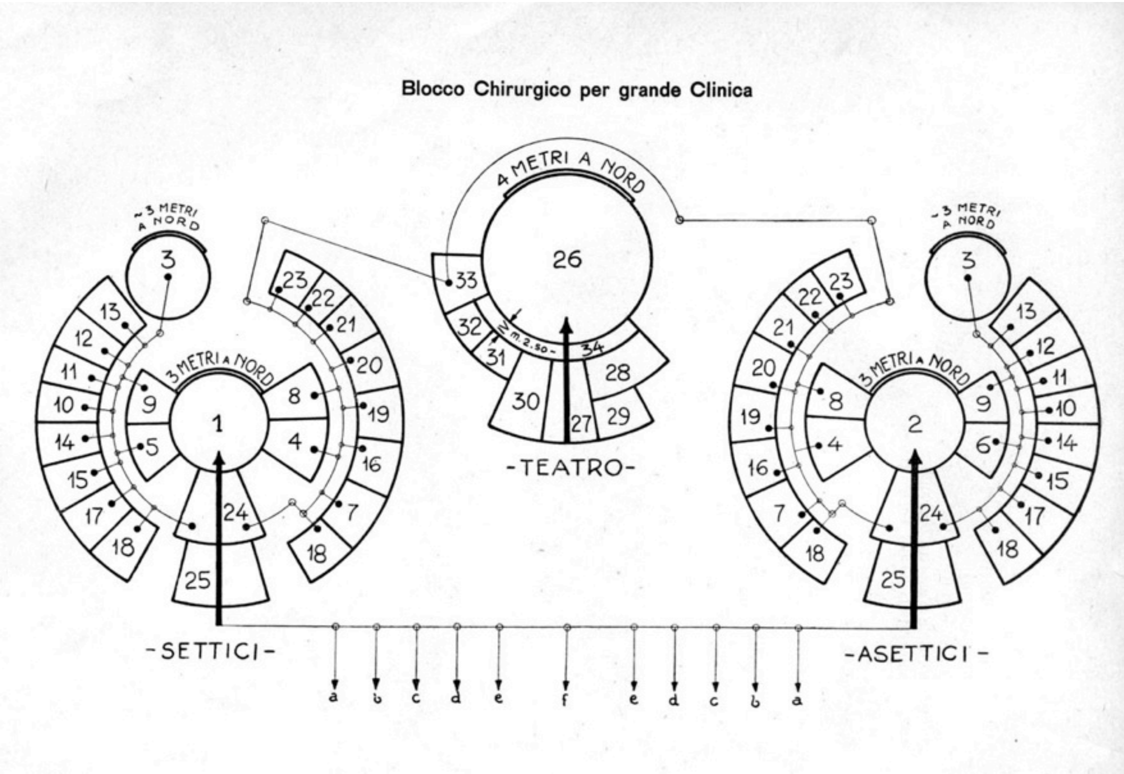

Figure 13 – G. Vaccaro – Distributive scheme for a large clinic[61]

This method has been taught in many faculties of engineering and architecture. In fact, until recently the reason why many architects have been comfortable with using diagrams is due to the diffusion of handbooks like that of Neufert, which are designed to characterize typological layouts in general.

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[60] Vaccaro, 1933.

[61] Vaccaro, 1933, p. 22.

2.2.3 Modern methods of design and process solving

In the early ’60s, Christopher Alexander published the influential book *Notes on the Synthesis of Form*, in which he described the need for rationality in the design process. If design is a conceptual interaction between the context's demands and the inadequacies of the form, he argued, there may be a way to improve it by making an abstract picture of the problem that retains only its abstract structural features. As a mathematician, he introduced set theory, structural analysis and algorithms as tools for addressing design problems.[62] At the time, these were only partially implemented with computers, due to the high cost of the technology required.[63]

Researchers began to experiment with computers in the field of architecture in the late sixties. *“One of the areas where the computer can be helpful to an architect is in space allocation, in finding a large number of possible schemes at a sufficiently early stage of the design process, and choosing the best one for further development”*.[64] But the main problem was the *“high number of constraints that have to be simultaneously taken into account in solving a design problem, and it was difficult to find a method to consider them all. Moreover, the only way to arrive at a conclusion was to break down the problem into sub-problems and use a non-deterministic approach”*.[65]

After a few years, the idea arose to attempt a new way to approach design problems using “linguistics” and “logic”. In this instance, the designer confronts the problem through decomposing its structure by grouping constraints into thematic areas (e.g. zoning, circulation), and then considering each group of constraints more or less independently. This information, converted into sentences, allows for the consideration of not only singular elements but also the rules and relationships for achieving a meaningful composition.[66]

Also in the ’60s, Markov elaborated another type of approach with regard to the use of algorithms, using grammar-like rules to operate on strings of symbols. He suggested that any algorithm should be definitive, universally understandable, general and conclusive. Algorithms have been written for designing parts of buildings. Some researchers and

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[62] Alexander, 1964.

[63] Very few research centres had a computer and if they had one, the interest in research was directed towards the electronic, mechanic and aeronautic fields, rather than the architectural.

[64] Terzidis, 2001.

[65] Broadbent, 1970.

[66] Terzidis, 2001.

theorists have opposed the algorithmic approach because often the information needed is inaccurate or unavailable and the result produced is ill-defined.[67]

In overcoming this issue it is possible to consider the computer not as a solver of complex mathematical operations relating to a predetermined pattern, but as a direct aid to the designer through a man–machine dialogue. This requires a refinement of the computer's ability to “learn” and criticize the choices of the architect.

The success of this method has been proven by results obtained at MIT and other research institutions in the U.S., and does not require the operator to use algorithms.[68] The main difference with the model method is that the computer does not hold the optimal solution, but its output presents a series of verifications required by the designer (for instance, building regulations, circulation, exposure, etc.), with any alternatives proposed for the same class of solutions and a rapid return (for now, schematic) according to the major systems of representation.

The way in which the human brain differs from the computer is precisely what makes it more efficient during the design process. In terms of learning ability, memory, precision and operation of an algorithm the computer is more efficient than the brain. But the brain will always be superior whenever it has to make a judgement of value, recognition of form or association of ideas. In other words, the most efficient design process is one that is able to use the brain and the computer in a symbiotic relation.[69]

It is well documented how the creative act evades deterministic analysis, associational concepts and structuralism.[70] According to Coons, the design process is a complex phenomenon consisting of intricate nodes in which intuitive imaginative and analytical, mathematical and rational processes are in dialogue.[71] In his work he explains that human reason always shows a great ability for invention, building, comparison and judgement; but is extremely inefficient in executing rational processes that require the manipulation of a number of interrelated data in a complex way. On the other hand, computers are particularly efficient on an analytical level, but completely lack the ability to create. The most logical thing seems to be to find a way of merging the creative capability of the human brain and the analytic and computational capability of the machine.

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[67] Gill, 1978.

[68] Negroponte, 1970.

[69] Broadbent, 1970.

[70] Deterministic analysis is usually only valid in the scientific process, in the process of associations according to which the idea grows by association and selection in a rapid series of trial and error; structuralism refers to the formulation of a Gestalt to reconcile determinism with associative ideas.

[71] Coons, 1964.

The initial project idea, having been subjected to a process of logical clarification, can be transformed into a concept to which precise analytical instruments can be applied. The concept is modified through a process of cyclical feedback (Figure 14). This feedback mechanism ends when a positive level of value judgment is achieved. During the design process, the designer chooses a number of variables, which may be structured as block diagrams, linear graphs and so on.

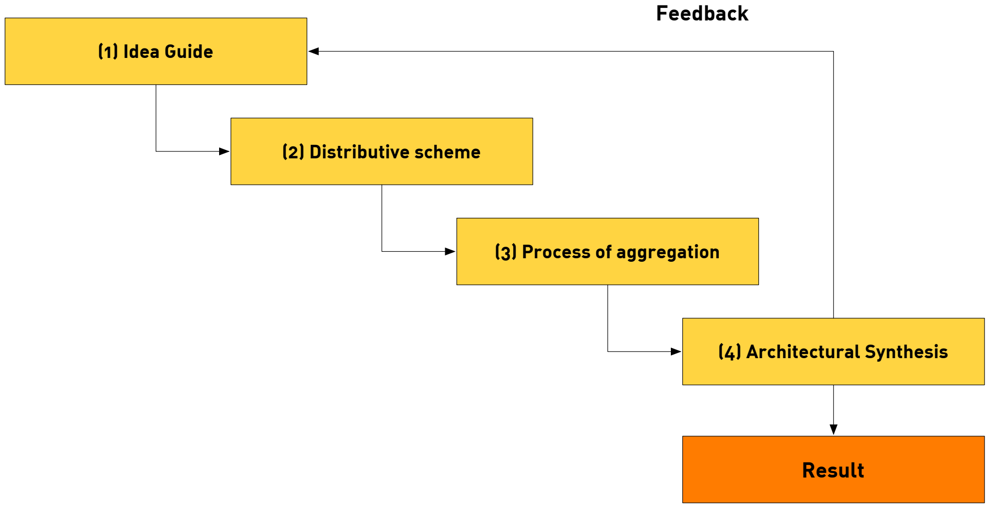


Figure 14 – Design feedback

Another type of approach that was experimental and partially implemented through experiences with the computer has made it essential to use "heuristic approaches": *"Design synthesis methods are typically inspired by the analogies and guided by the architect's own or another designer's previous experience"*.[72] Techniques of trial and error are usually the basis for a heuristic approach to a solution. In fact, this technique is closer to the "search-and-evaluate" process used in architectural design than any other type.

When synthesizing the design solution, one of the most common heuristic methods is to "borrow" from other knowledge areas which appear to hold some relevance to the problem. For instance, Philip Steadman in 1974 was the first to propose borrowing a metaphor from electrical networks to guide the computational synthesis of architectural form. He found a surprising similarity between a specially constructed graphical representation of architectural floor plans and the physics of electricity, as expressed by Kirchhoff's law of electrical flow.[73]

A similar metaphor was presented by Arvin and House,[74] who proposed an analogy with mechanical springs, applying *"the principle of dynamic motion and geometrical*

[72] Kalay, 2004, p. 255.

[73] March & Steadman, 1974.

[74] Arvin & House, 2002.

deformation to rigid and non-rigid objects for the purpose of simulating realistic behaviour and visual effects".[75] Topological design objectives such as adjacencies between spaces and relationships between them could be expressed by the strength of a spring that is linked to the barycentre of a space.

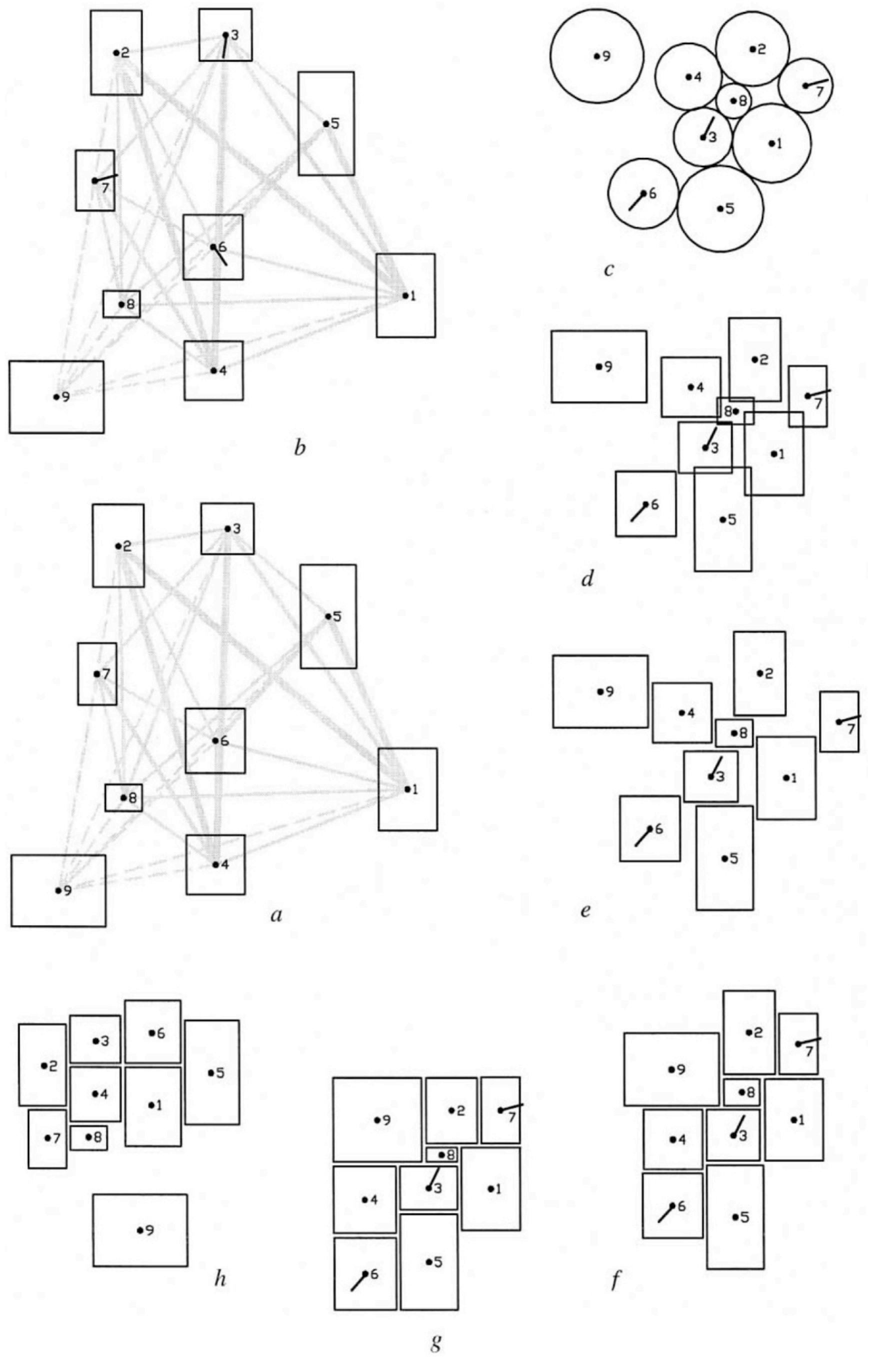


Figure 15 – Arvin and House – Results achieved[76]

[75] Kalay, 2004, p. 259.

[76] Arvin & House, 2002, p. 222.

Instead, many researchers[77] affirm that the most common approach to the synthesis of new design solutions is to look at case studies because it is believed that the problem currently under investigation is not fundamentally different from a similar problem that has been encountered in the past.

2.2.4 Graph Theory and architecture

Representing architecture through graphs is a way of simply presenting a complex amount of data and can provide a better overview of a project.[78] Graph Theory makes it possible to analyse specific topics in the architectural composition, such as economy and efficiency of layout distribution and circulation paths.[79] It is also useful to implement algorithms to create an automated layout distribution.[80] Moreover, to evaluate the efficiency of a particular path it is possible to calculate specific indices and measurements deriving from Graph Theory, which can then be easily implemented using mathematical software.[81] From a mathematical point of view, a graph G is composed of a set of vertices (v) and a set of edges (u).[82] Reciprocal relations of exchange connect all of these nodes (Figure 16).

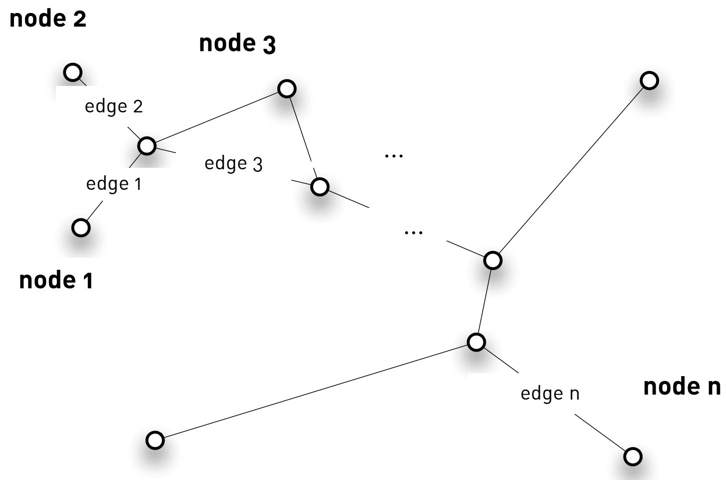


Figure 16 – Example of a generic graph

[77] We can cite many research examples: Do E. and Gross M. D "Reasoning about Cases with Diagrams", 1996; Flemmings U. "Case – Based Design in the SEED system", 1994; Riesbeck C.K. and Schank "Inside Case-Based Reasoning" 1989; Kolodner "Improving Human Decision Making though Case-Based Decision Aiding", 1992.

[78] Blanco & Pisonero, 2001.

[79] Scarano & Piemontese, 1997.

[80] The graph-theory based model was studied by many researchers as a way of representing and solving problems. We can mention: Schwarz et al., 1994; Liggett, 2000; Arvin & House, 2002.

[81] See Appendix B.

[82] Bondy & Murty, 1976.

In some cases a loop may exist within a graph: this happens when two or more edges connect the same pair of vertices, or when an edge joins a vertex to itself.[83]

In layout design, a vertex represents a specific space within a layout distribution, and an edge represents the relationships established between these spaces. This method of abstracting and converting any layout distribution into a graph must be generalized and must take many aspects into account.

The **support structure** is the result of an analysis of the topological relationships between elements: the activity (complex or elementary), functions and spaces are defined, classified and ordered in order to build a list of preliminary information. Operationally, this phase continues through the assembly of an adjacency matrix in which the intersection of the raw represents a connection between spaces. An adjacency matrix is an n × n matrix in which the non-diagonal entry a_{ij} is the number of edges from vertex i to vertex j, and the diagonal entry a_{ii}, depending on the convention, is either once or twice the number of edges (loops) from vertex i to itself. If the graph is undirected, the adjacency matrix is symmetrical.

$$A = \begin{array}{c} \\ S_1 \\ S_2 \\ S_3 \\ \vdots \\ S_n \end{array} \begin{array}{c} \begin{array}{ccccc} S_1 & S_2 & S_3 & \cdots & S_n \end{array} \\ \begin{bmatrix} - & 1 & 0 & \cdots & 1 \\ 1 & - & 1 & \cdots & 0 \\ 0 & 1 & - & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 1 & 0 & 0 & \cdots & - \end{bmatrix} \end{array}$$

Equation 1 – Adjacency Matrix Graph A

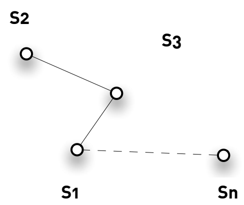


Figure 17 – Graph A

The scheme created is a lattice with unitary modules, in which every vertex of the graph is associated with one or more modules, depending on the needs of the adjacency of the element in question.

According to Rodrigue and Ducret,[84] it is possible to use several measures and indices to analyse network efficiency. Many of them were derived from the work of Kansky and can be used for:

1. Expressing the relationship between values and the graph structures they represent;
2. Comparing different graphs (in terms of transport);
3. Comparing the evolution of a graph in different points and in functions of time.

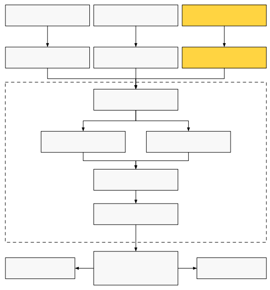
[83] Bondy & Murty, 1976.

[84] Rodrigue & Ducruet, 2013.

In studying a graph it is possible to calculate an index and measurements that mainly refer to two different scales: the “graph scale” and the “node scale”. In describing a graph it is possible to analyse several measures and attributes that characterize it: for instance the diameter, the number of cycles and the order of a node that characterize the graph. On the node scale some parameters are based on links with adjacent nodes, while others on the “global level” consider the node’s situation in the whole network.[85]

[85] The parameters used for this research are described in Appendix B.

2.3 Information and communication technologies



Nowadays the methods of design are totally interlinked with technology: it is no longer be possible to imagine the representation and communication of information without a computer-aided design (CAD) system.

Although it is also possible to design in a traditional way, the advantages in terms of time and reduction of errors have made the CAD system a favourite system with professionals. The CAD gives the opportunity to increase the quality of the drawing, reducing the time for correcting and updating the information. Through three-dimensional CAD software it is also possible to represent the geometry of any artefact and the form of a building. Furthermore, complex architectural shapes cannot possibly be represented and analysed without the permanent support of the computer.

When representing and managing complex geometry there are two general categories: Constructive Solid Geometry (CSG) and Boundary Representation (B-rep).

The CSG allows us to “construct” complex solids by combining simpler ones. For instance a shape can be easily generated through the union, intersection and difference between solids. Original shapes used in this process of generation, such as the cube, the cylinder, the block and the sphere, are called “primitive”. This method is suitable when the objects are made from identifiable primitive shapes (generated from dimensional parameters) that are added or subtracted to make complex shapes. If mechanical parts are conformed to this parading, historical architectural compounds may be approximated to a specific primitive but in general they do not fit in this category due to their complexity and infinite variety of shapes.[86]

The second approach is expressed by the boundary representation (B-rep) that consists of a high hierarchical collection of vertices, edges and faces. The volume can be calculated through its boundary surface but this last has to obey restrictive rules: it must be closed and it must not self-intersect. Although this last approach seems to be more manageable in terms of storage space, it is more difficult to model, manipulate and interrogate.

Instead, a building or its compounds can include more than one geometrical features. It must also contain non-geometric attributes, such as the cost, the material and the producers, as well as physical characteristics relating to specific conditions (such as transmittance, reflectance of surface, fire resistance, etc.).

[86] Kalay, 2004, p. 144.

Only after this association through parameters will it be possible to carry out specific analysis such as cost estimation, energy consumption, seismic analysis and the building's behaviour in this scenario, and so on.

All of this information is contained in a complex database where homogenous categories are codified through building standards. Usually this information is subdivided into classification, descriptive, behavioural, functional, locational and constraint information.

In this context, Building Information Modeling (BIM) is maturing as a new paradigm for storing and exchanging information about the construction components of a new building. Its adoption *"facilitates a more integrated design and construction process that results in better quality buildings at lower cost and reduced project duration"*.[87]

Another definition of BIM can be found in the international standards as *"shared digital representation of physical and functional characteristics of any built object (…) which forms a reliable basis for decisions"*.[88] BIM is realized with object-oriented software and consists of parametric objects that represent building components.[89] These elements have geometric or non-geometric attributes with functional, semantic or topologic information.[90]

2.3.1 BIM and existing buildings

Dealing with the transformation of a historical building often means addressing several difficulties raised in the early survey stages. Historical buildings are usually not easy to represent as a pure shape: vertical walls are not perpendicular, both in plans and in elevation, while spaces are distributed over different tiers that assume complex configurations.

When hypothesizing the process of re-designing an existing building, the information managed through a computer-aided design system can be subdivided into two main approaches: the former, a defined "reality-based model", consisting of a 3D digital reproduction of the artefact; the latter, a "virtual prototype", a conceptual representation expressed in parameters.[91]

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[87] Eastman, et al., 2011, p. 1.

[88] ISO standards, 2010.

[89] Eastman et al., 2011.

[90] The element can have (1) functional attributes, such as cost and time of installation or (2) semantic information, such as connectivity, aggregation, containment or intersection information, as well as (3) topologic attributes such as locations, adjacency, complanarity or perpendicularity.

[91] Usually the B-rep and mesh representations are used in the first category to achieve a useful complex model for the phase of rendering. CSG is usually applied in the second case.

In general BIM has gained general approval around the world after political decisions to make it mandatory for projects of a certain size.[92] However, although BIM-related publications oriented towards new construction are experiencing a surge in popularity, in the literature it is clear that little research has focused on the re-design of existing buildings and interventions relating to pre-existence.[93] According to Volk, this is due to three main aspects: (1) high modelling/conversion effort from captured building data into semantic BIM objects; (2) updating of information in BIM; and (3) handling of uncertain data, objects and relations in BIM occurring for existing buildings.

The first point is connected with all aspects of the survey technology. From a points clouds, realizable with laser scanners or photogrammetry, it is possible to extract a BIM model and leave the point clouds as a geometrical reference. The main issue is to understand what the distance should be between geometrical references and BIM representation (in this case a simplified version).

The second point is concerned with the phase of updating the information into a BIM. Updating and managing information for an existing building is more time-consuming than simply modelling. Moreover, intervention on existing buildings is usually localized to a few parts of the building and does not justify a massive effort for an extensive use of BIM.

The third point is strictly related to the internal composition of all the compounds in a building. Often this point is connected to the gathering of information, finding all the historical sources and conducting specific local analysis. Once the information has been collected, it is then necessary to understand how to manage it as regards the building.

On the other hand, however, potential benefits can be achieved using BIM for FM. The model can be used as a depository or store for the historical information about all the modifications that the building undergoes, managing all the processes of maintenance.[94] Depending on the type of objective that we want to achieve, it is possible to set the level of detail and the level of accuracy that a BIM must have. The level of detail is connected to the level of exchangeable information, both numerical and graphical, required during the process. It can happen that it is possible to solve certain issues using only conceptual volume rather that inserting all the specific compounds.

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[92] BSI is publishing a new standard to encourage best practice implementation of Building Information Modelling. BIM is already mandatory for many countries (see chapter – BIM implementation in public sectors)

[93] Volk et al., 2014, p. 110.

[94] A recent example of implementation was carried out by the Manchester City Council for the BIM-FM implementation of the Town Hall Complex and was published in Codinoto et al., 2013, to which the author of this PhD thesis has contributed.

If we refer to a methodology already elaborated in 2011 by the author[95] that transposes the directives of the Finnish BIM guidelines[96] to an Italian context, there are several levels of BIM models, subdivided into the following categories:

1) **Conceptual BIM:**
   a. Spatial BIM Group SG-BIM
   b. Spatial BIM S-BIM
2) **Constructive BIM:**
   a. Preliminary BIM P-BIM
   b. Building Element BIM BE-BIM
   c. As Built BIM A-BIM
3) **Facility Management BIM** FM-BIM

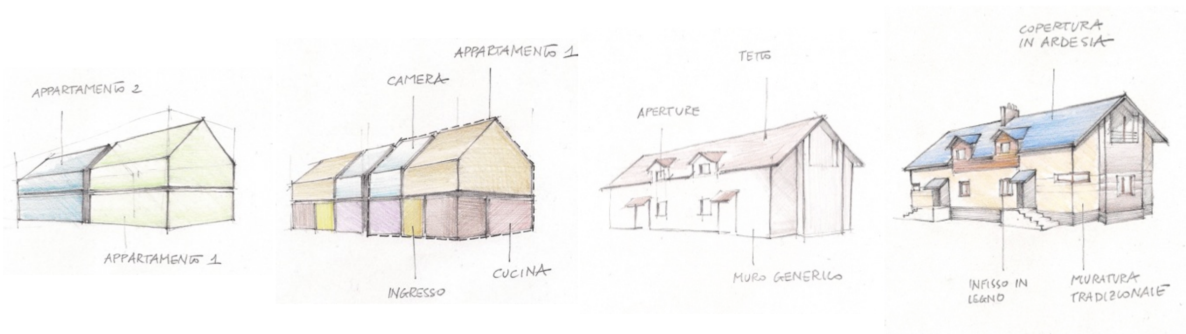

Figure 18 – Example of SG-BIM, S-BIM, P-BIM and BE-BIM

The first model Spatial BIM Group (SG-BIM) is based on macro areas and volumes, modelled in accordance with urban project constraints. This level corresponds to the lowest level of detail that the project may have. The BIM files can be arranged individually or through groupings of files, according to the size of the project (for example, large complex designs can be divided according to functional areas). The heights of the solids modelled may be considered as deriving from the gross or net volume (the volume will include all the external partitions, both horizontal and vertical). Furthermore, at this stage, the outer casing must be inserted. It is not necessary to model structural elements and internal components.

Spatial BIM (S-BIM) consists of similar procedures to SG-BIM, with the difference that in this step there is a program to fit in the previous volume. The groups are divided into

[95] Donato, 2011.

[96] Senate Properties, 2007.

space units, which are modelled as independent objects. In the architectural plan, these units are grouped into sectors (for instance, functional units or fire departments). Even at this stage, no information has to be added regarding the detailed construction system, technology and plants. Information relating to the structure and facilities can be entered via the external model.

The third model is the Preliminary BIM Building Element (PBE-BIM), which allows the initial addition of information regarding building components, divided into internal and external partitions, vertical and horizontal, shell and fixtures. Each of these objects is characterized by their nominal dimensions and their functionality (only in the next step will features about finishes, materials, details, installation dimensions and tolerances be added). In addition, all objects refer to a progressive code that indicates the reference of the plan and code of the object (for example, "wall-107" indicates a wall on the first floor having code 07). This fact is not trivial because it imposes a modelling by tiers: for example, the walls and the space for each floor must be modelled separately.

The fourth model, BIM Building Element (BE-BIM), contains all the detailed information about the building elements (e.g., information about stratification of walls, ceilings, roofs, etc). Usually this model has to be used in the tendering phase, without indicating the type of product supplier. The BE-BIM also includes specialist contributions subdivided into architecture, structure and MEP (mechanical, energetic and plumbing). This last is subdivided again into HVAC (heating, ventilation and air conditioning) systems and electrical systems.

For all of these phases a phase of "model checking" must be performed that allows the design team to evaluate the consistency of the models according to two main aspects: at the scale of the object, each element inserted into the BIM has to be checked in order to ensure the uniqueness of the data (thus avoiding repetition and errors) and, at the building scale, the models have to be coherent between the different specialist models (architecture, structure and MEP). It is possible to use dedicated software that can perform automated verification on the coherence of the data to perform this check.

Moreover, after the phase of construction there is a phase of updating the BIM model, inserting all the final information about the real product that was installed. This model can then be used for the next phase, which in general is defined as Facility Management.

2.3.2 Implementation of BIM in public sectors

This section describes the current implementation of BIM in several countries. There are different levels of knowledge about BIM and different levels of development. Moreover, in some countries it is mandatory and they have provided for this with the establishment of “BIM guidelines” that are reported in the following section. In other countries, however, BIM is not promoted at all. References for more detail can be found in the work of Bolpagni.[97]

This section will include a brief discussion of the situation of some nations that are working with or are going to implement BIM in the public sectors: USA, Finland, UK, Singapore, Norway, Denmark, Netherlands, South Korea, Hong Kong, Australia, New Zealand, Iceland, Estonia, Sweden, Germany, China and Italy.

In the **USA**, the “General Service Administration” (GSA), through its Public Buildings Service Office of Chief Architect, established a National 3D-4D-BIM Program in 2003.[98] The National 3D-4D-BIM Program promotes value-added digital visualization, simulation and optimization technologies for developing quality and efficiency during the lifecycles of projects. Since 2007 GSA has required spatial program BIMs for all major projects as a minimum requirement for submissions for final concept approvals. Moreover, all GSA projects are encouraged to utilise 3D, 4D and BIM technologies. GSA published a Series of Guidelines related to 3D-4D-BIM Overview, Spatial Program Validation, 3D Laser Scanning, 4D Phasing, Energy Performance and Operations, Circulation and Security Validation, Building Elements and Facility Management[99] In addition to the GSA guidelines, other US BIM Guides are published by states, and by institutions like universities. In 2011 the US Army Corps of Engineers published a “Building Information Modeling (BIM) Roadmap. Supplement 2 - BIM Implementation Plan for Military Construction Projects, Bentley Platform”. In 2009 the Associated General Contractors of America published the second edition of “The Contractor’s Guide to BIM” (first edition published in 2006), which analyses the implication of BIM for contractors, based on experience provided by contractors who have already adopted BIM.[100] The US Coast Guard has embraced the utilization of BIM.[101] The National Institute of Building Science

[97] Bolpagni, 2013.

[98] Klemlani, 2012.

[99] Bolpagni, 2013.

[100] Eastman et. al., 2011, p. 301.

[101] Succar, 2009, p. 360.

has used BIM since 2007, and recently it published the second version of "National Building Information Modelling Standards".[102]

Finland has a to of experience in BIM-based processes and in 2007 the Finnish unincorporated state-owned enterprise Senate Properties, published its Requirements and Guidelines, which were updated and replaced by the "National Common BIM Requirements" (COBIM) in 2012. The aim of these requirements is to define more precisely what is being modelled and how the modelling is done during all the phases of a construction project to support the parties involved. The documents are available on the Finnish section of the website of BuildingSMART.[103] Finland can be considered a leader in BIM due to its long experimentation with using BIM in public procurements. Senate Properties has carried many pilot projects and studies about BIM implementation since 2001. After evaluating the benefits of using BIM, around 2007, the company decided to adopt BIM and IFC standards for both the construction and renovation of ordinary projects. Moreover, the architectural design is used to study alternatives based on space models and to prepare the tender documents for the contracting stage.[104] During the project planning stage, BIM supports investment decisions, the quantities extracted from the model are adopted to assist the production phase, and it is also useful for energy simulations.

The **United Kingdom** began to implement BIM a few years ago to explore new ways of controlling construction costs and overcoming financial problems. In May 2011, the Cabinet Office published its "Government Construction Strategy", which stated for the first time that the "Government will require fully collaborative 3D BIM (through all electronic documentation and data) as a minimum by 2016".[105] The UK Government wants to strengthen the public sector's client capability in BIM implementation so that all central government department projects will be adopting at least Level 2 BIM by 2016.[106] Moreover, the Cabinet Office will develop standards enabling all members to work collaboratively because the *"lack of compatible systems, standards and protocols, and the differing requirements of the clients and lead designers, have inhibited widespread adoption of a technology which has the capacity to ensure that all team members are working from the same data"*.[107] Indeed, the AEC (UK) BIM Standard Committee[108] released several BIM standards for BIM software such as Revit, Bentley and ArchiCAD, to

[102] National Institute of Building Science, 2014.

[103] http://www.en.buildingsmart.kotisivukone.com/3

[104] Bolpagni, 2013.

[105] Cabinet Office, 2011, p. 14.

[106] Cabinet Office, 2012, p. 6.

[107] Cabinet Office, 2012, p.13.

[108] http://aecuk.wordpress.com/.

help AEC UK firms to migrate from CAD to BIM. The aim of the UK strategy is to promote the public sector as a better client, *"more informed and better co-ordinated"*, and to change the current business models and the industry's way of working.[109] A BIM Task Group was created to support the work of the Government Construction Strategy, and it has progressed rapidly in developing practice and in implementing the policy, putting the UK in a leading position amongst national governments.

Singapore was one of the first government organizations to develop model-based design, through its "Building Construction Authority" (BCA).[110] In the early 1990s, the authority worked towards the development of automated code checking, named "CORENET", and BIM will become mandatory in 2015. Since 2011 the BCA has accepted Architectural, Structural and MEP BIM e-Submissions.[111] Through its website it is possible to download templates and guidelines compatible with the main BIM software such as Revit, ArchiCAD, Tekla Structure and Bentley. Moreover, BCA is developing a library of buildings and design objects. In June 2010 it introduced financing for training, consultancy, software and hardware, and it also encourages BIM courses at universities and organizes BIM workshops and seminars.[112] The last version of the BCA publication was published in August 2013 (version 2.0),[113] published together with "BIM Particular Conditions Version 2.0".

In **Norway**, the "Statsbygg" (the Norwegian government agency) adopts BIM for all its new building projects. In 2011 it published a new version of its guidelines, the Statsbygg Building Information Modelling Manual Version 1.2 (SBM1.2), based on previous versions and on past experience. The aim of SBM1.2 is to describe Statsbygg's requirements for dealing with the adoption of BIM and IFC formats. It contains both generic and discipline-specific requirements which can be normative or just informative. Building Information Modelling 90 has been used by design teams, clients, facility managers and domain practitioners involved in the process. Moreover, SBM1.2 may also guide software application providers.

In **Denmark,** from 2002 to 2007, the "Danish Enterprise and Construction Authority" carried out a Digital Construction Initiative to develop common standards and guidelines for digital construction projects.[114] In 2007 it decided to adopt BIM requirements for

[109] Cabinet Office, 2011, p. 3.

[110] http://www.bca.gov.sg/bim/bimlinks.html

[111] http://www.corenet.gov.sg

[112] Klemlani, 2012.

[113] BCA, 2013.

[114] Steffensen, 2012.

governmental projects[115] (with some requirements: "the Danish Building Classification System; project web-system for exchange of digital information on building projects; 3D-models (BIM) in competitions, design and construction; digital bidding and tendering (based on 3D-models); hand-over of relevant, digital information at the end of the building process; IFC-format for data exchange). In June 2011 the Danish Parliament decided to extend the mandatory adoption of BIM to all local and regional projects worth over 2.7 million euro.[116]

In **the Netherlands** the **"**Rijksgebouwendienst BIM Standard", published in 2012 by the Dutch Ministry of the Interior and Kingdom Relations, is the document that established the adoption of BIM. There is also an English version of the BIM Standard.[117] The document describes the specifications of BIM extracts and accompanying deliverable files but it does not show either the step-by-step instructions for achieving a result in compliance with these specifications, or a BIM or CAD manual.[118]

In **South Korea**, there is the "South Korea Architectural BIM Guide v 1.0"[119] and the "National Architectural BIM Guide".[120] South Korea's Public Procurement Service made the adoption of BIM mandatory by 2016 for all projects over S$50 million and for all public sector projects.[121] Moreover, in 2010 the Public Procurement Service published an "Architectural BIM Guide" to reduce the burdens on the industrial market resulting from the necessary adaptation to the new technology. BIM is adopted at each design stage and for building energy efficiency, energy simulation and basic quantity take-off.

In **Hong Kong**, there is the "Hong Kong BIM Standards Manual" for the Development and Construction Division of the Hong Kong Housing Authority[122] and the "BIM Library Components Design Guide" for the Development and Construction Division of the Hong Kong Housing Authority.[123] The Hong Kong Housing Authority has been piloting BIM since 2006 and it requires BIM for all new projects from 2014. It has also developed a set of BIM standards, a user guide, a library component design guide and references for effective model creation, management and communication among BIM users.[124]

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[115] Wong et al., 2009.

[116] BuildingSMART, 2011.

[117] Rijksgebouwendienst, 2012.

[118] Rijksgebouwendienst, 2012, p. 5.

[119] http://www.buildingsmar t.or.kr/Document/BIM_Guide_vol1_KoreaPPS_2010_eng.pdf.

[120] http://www.buildingsmart.or.kr/ Document/BIM_Guide_MLTL_Korea_2010_eng.pdf.

[121] Build Smart 2011, p. 3.

[122] http://www.housingauthority.gov.hk/en/business-partnerships/ resources/building-information-modelling/index.html.

[123] http://www.housingauthority.gov.hk/en/business-partnerships/resources/%20building-informationmodelling/index.html.

[124] Build Smart, 2011, p. 4.

In **Australia** we can find the "National Guidelines for Digital Modelling" [125] from 2009 and the "National Building Information Modelling Initiative Volume 1:Stategy".[126] In 2009 the Cooperative Research Centre for Construction Innovation published two guidelines related to National BIM Guidelines and Case Studies. [127] Moreover, in 2012 BuildingSMART Australasia published a National BIM Initiative to drive the construction industry into a new efficient, low carbon era of BIM. This recommends that industry and the Australian Government work together to promote initiatives that will accelerate the adoption of BIM in Australia and ensure the growth of the construction sector. At the BuildingSMART Australasia website [128] the Department of Defence of the Australian Government recognizes BIM's benefits and is going to integrate BIM and IPD into its projects. Indeed, it will adopt 3D, 4D and 5D together with new forms of contracts.[129]

In **New Zealand**, we can find the "New Zealand National BIM Survey 2012". In 2012 the government established an initiative called the "Building and Construction Productivity Partnership" to improve productivity in the building and construction industries by 20% by the year 2020.[130] However, the government does not require BIM yet.

In **Sweden**, even if BIM is not mandatory, five public companies (Akademiska Hus, Fortifikationsverket, Riksdagsförvaltningen, Specialfastigheter Sverige and Statens Fastighetsverk) are collaborating to establish demands and standards regarding BIM adoption in their projects. [131] Moreover, public clients such as the Royal Institute of Technology (KTH) and the Stockholm Country Council have demanded the adoption of BIM in their projects.[132]

The implementation of BIM in **Germany** is still in the early stages even if software vendors are already offering BIM solutions, some general contractors are adopting it and some pilot projects for public authorities are taking place. [133] In 2010 the German Government der Forschungsinitiative Zukunft Bau (Bundesinstitut für Bau, Stadtund Raumforschung) organized a Research project called "BIM – Potentials and Barriers".[134] The aim of this project was to investigate the BIM situation in Germany, together with the

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[125] http://www.construction-innovation.info/images/pdfs/BIM_Guidelines_Book_191109_lores.pdf.

[126] BuildingSMART Australasia, 2012.

[127] http://www.construction-innovation.info/index6d6d.html?id=1083.

[128] http://buildingsmart.org.au/thenational-bim-initiative.

[129] http://www.bimmepaus.com.au/libraries/resources/Forum202013/bimmepaus%20presentation%20-%2023%20jul.pdf.

[130] Page and Curtis, 2012, p. 5.

[131] Lindblad, 2013, p. 61.

[132] Idem, p 32–34.

[133] Both, 2012, pp. 1–2.

[134] Idem.

benefits and barriers related to its development. Representatives from public authorities, practice, AEC associations and buildingSMART took part and prepared a questionnaire to analyse the current situation. The results show a restricted development of BIM and a general scepticism about BIM.

BIM in **China** is not mandatory and it is not mentioned in the five-year plan manifesto. However, China is interested in the energy efficiency of buildings, which is not possible without a model-based representation of the facility. For this reason Khemlani [135] says that China is indirectly encouraging the adoption of advanced technologies such as BIM.

Italy does not require BIM and the current situation is based on the traditional exchange of information using digital/paper-based documents, although Italy is a member of buildingSMART. In July 2011 the Italian government funded a research project called InnovANCE[136] to create the first national database of technical, scientific and economic information useful to the AEC industry. However, it did not include a BIM policy and for this reason in October 2012 Azzone, Buzzetti, Squinzi and Torretta wrote an article to push the Government into adopting BIM tools, interoperability standards and simplifying the normative to improve the current situation of the public works process.

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[135] Khemlani , 2012

[136] Daniotti et al., 2012; Ciribini, 2011.

2.3.3 Standards related to BIM and existing buildings

This section presents a list of international standards (mostly European) related to BIM and existing buildings.

- **ISO/TS 12911:2012** – Framework for building information modelling (BIM) guidance
- **ISO 29481-1:2012** – Building information models – Information delivery manual – Part 1: Methodology and format
- **ISO 29481-2:2012** – Building information models – Information delivery manual – Part 2: Interaction framework
- **ISO 15886-4:2014** – Building Construction – Service Life Planning – Part 4: Service Life Planning using Building Information Modelling
- **ISO 7518:1983** – Technical drawings – Construction drawings – Simplified representation of demolition and rebuilding
- **ISO 21929-1:2011** – Sustainability in building construction – Sustainability indicators – Part 1: Framework for the development of indicators and a core set of indicators for buildings
- **ISO 15686-1:2011** – Buildings and constructed assets – Service life planning Part 1: General principles and framework
- **ISO/PAS 16739:2005** – Industry Foundation Classes, Release 2x, Platform Specification (IFC2x Platform)
- **BS 1192:2007**
- **PAS 1192:2013**
- **PAS 1192-3:2014**
- **ISO/DIS 16757-1 DRAFT**
- **BS 1194-4** Available for public comment
- **ISO 16739:2013** Industry Foundation Classes (IFC) for data sharing in the construction and facility management industries
- **ISO 5127:2001** Information and documentation – Vocabulary
- **UNI 11337:2009** – Building and civil engineering works Codification criteria for construction products and works, activities and resources
- **UNI 11150:2005** – Building Process: Definition of the process steps of renovation of existing buildings
- **UNI 8290:1981** – Residential Buildings: Definition of the process steps of renovation of existing buildings
- **BIP 2207 –** Building information management. A standard framework and guide to BS 1192
- **BS 6953:1998 (ISO 7078:1985)** Glossary of terms for procedures for setting out, measurement and surveying in building construction (including guidance notes)
- **BS 7000-4:1996** – Design management systems. Guide to managing design in construction

- **BS 8541-1:2012** – Library objects for architecture, engineering and construction. Identification and classificationCode of practice
- **BS 8541-2:2011** – Library objects for architecture, engineering and construction. Recommended 2D symbols of building elements for use in building information modelling
- **BS 8541-3:2012** – Library objects for architecture, engineering and construction. Shape and measurement. Code of practice
- **BS 8541-4:2012** – Defines properties and multiple levels of information including properties required for Specification and selection and environmental, cost and social impacts
- **BS 8541-5:2014** – IN DEVELOPMENT will cover assemblies – the sharing of sub-models representing combinations of components and spaces covering naming, classification and nesting
- **BS 8541-6:2014 –** IN DEVELOPMENT will cover product declarations – the sharing of data expected from product declarations, labelling and environmental tables. Aims to offer IFC and IFCXML and COBie representations including waste data in standardised printed forms
- **BS ISO 12006-2:2001** – Building construction. Organization of information about construction works. Framework for classification of information
- **BS ISO 12006-3:2001** – Building construction. Organization of information about construction works. Framework for object-oriented information
- **BS ISO 22263:2008** – Organization of information about construction works. Framework for management of project information
- **BS ISO 29481-1:2010** – Building information modelling. Information delivery manual. Methodology and format
- **BS ISO 29481-2:2012** – Building information models. Information delivery manual. Interaction framework

3 Related works

After a careful analysis of the state of the arts (concerning the principal topics of existing buildings, the design process and the ICT tools), it is now necessary to highlight other works of research that focus on the implementation of rules for re-designing existing buildings through automatic assessment. There are many such studies in the literature. For clarity, these may be subdivided into the following three groups:

1) Assessment of early design phase;
2) Software for model checking;
3) Research and independent software.

3.1 Assessment of early design phase

The major issue for a designer is controlling the complexity of the building during the design phase, and monitoring the frequent changes that have to be observed in order to comply with the law and regulations. In a traditional design path this process is often conducted by visual and manual checks, although this increases the monitoring times and also often generates errors.

The design phase usually begins a long time before lines are drawn on white paper or a sketch is made on the computer. It starts with the client's brief, which may be very detailed or extremely abstract. After this phase it is necessary to develop a detailed building programme (a "space programme") that lists all the spaces, groups or functions that are required in the building, as well as approximate areas, desired adjacencies, inter-relationships and any other specific requirements. For a small project, this phase is sometimes trivial due to the experience of the architect, but as the dimension of the project increases then the complexity of the building programme also grows, and experts are often called in to assist with this pre-design phase.

The **programming phase** is followed by the **conceptual design phase**, when the form is selected in tune with the development of a "space plan" that satisfies the programmatic requirements of the building. "Space planning" refers to the specific ability to create and manipulate spaces that are needed at the conceptual stage while leaving aside temporary building elements like walls, doors and windows. In this phase the spaces are considered on a very abstract level.

Some studies are oriented to understanding the potential of *"a new generation of software tools that can automate the checking of compliance with building codes, thus improving the efficiency of building design and procurement"*.[137] In fact, many highlight reviews of automated code compliance, identifying the key issues for future development.[138]

In particular, Chuck Eastman's "Automated Assessment of Early Concept Design",[139] commissioned by the Federal Government's General Service Administration (GSA) in 2009, described a possible method for automated assessment using BIM models. The method outlines a specific building function, the courthouse, and the GSA has a very well-defined design process for public buildings that is spelt out in its *P-100 Facilities Standards for the Public Buildings Service design guide*. Using this, the preliminary design solutions proposed by architects could be assessed and checked against specific criteria.

Recently architects have begun to submit Preliminary Concept Designs in the form of 3-D building models, which means their proposals can be partially assessed automatically. The concept design can now be generated using any of the GSA-approved BIM design tools. Currently these include Revit, Bentley Architecture and ArchiCAD, but others such as Digital Project, Vectorworks and Allplan are also being considered.[140]

The AEC Laboratory at Georgia Tech has defined the minimum required information for a "Preliminary Design Concept" for automatic assessment. The information needed is related to the definition of the spaces for each floor, distances between spaces, exterior walls and percentages of glazing, but does not include information about the construction material or orientation of the building on the site.

The IFC file can also be automatically assessed through a Solibri Model Checker, a specialist software for model checking. The rules implemented, as described in Eastman's article, are:

1) **Spatial validation of the layout**, comparing target counts and areas of the courthouse project space programme with those of the proposed concept design.
2) **Circulation analysis of the layout**, based on the courthouse-specific criteria of the US Courts Design Guide.
3) **A preliminary energy assessment**, using the Energy-Plus analysis tool.
4) **A preliminary cost estimate**, using the PACES cost estimating system.

[137] Greenwood et al., 2010.

[138] Xiangyang et al., 2010.

[139] Eastman, 2009.

[140] Idem.

During spatial validation, the challenge is to compare alternative layouts with the target requirements of the space programme, while also bearing in mind the requirements established by the GSA. The evaluation is made using an Excel data sheet, in which all the values included in the various cells of a specific candidate design are verified against the existing space programme.

The second task, the analysis of circulation, consists of evaluating the three separate circulation systems required for the design of a courthouse. One is for the public, another for judges, jury and court staff, and the third for defendants and US marshals. All these paths are crucial in shaping the building.

A visual method for analysing the paths:

Spaces are grouped into sets that are adjacent and have the same security. The connectivity of these zones is represented as solid edges, vertical access as dotted edges. If the specific circulation rule requires accessibility within a security zone and floor, then the vertical connections are disregarded.[141]

In many other studies, however, the problem of implementation is related purely to the application of defined rules within specific software for model checking.

3.2 Software for model checking

There are few examples of commercial software available for conceptual 3D modelling in the area of space programming and planning in the AEC technology industry, let alone for the automated management of space planning with BIM.

There have been many attempts to use 3D-modelling software in a very simple way for managing abstract form. For instance, some studies show automated layout distribution for factory building planning using LISP in AutoCAD; volumetric form can be modelled with intuitive software (like sketch-up); and sophisticated software (like Rhino and Grasshopper) can be used to automatically generate an automated distributive diagram representing a particular programme layout.[142] Few of these attempts are related to the evaluation of the programming phase.

For the specific issue of managing the programming phase and model checking there are two main commercial softwares: Solibrì Model Checker and Affinity, from Trelligence.

[141] Eastman, 2009, p. 55.

[142] This is the natural evolution of what is described in chapter 2.2.3 Modern methods of design and process solving.

Solibrì Model Checker[143] allows the designer to verify the quality of the IFC model and avoid errors during the design process. It is possible with this software to detect clashes between several models, present results and perform information take off. Moreover, *"every role has specific Rulesets, Classifications, and Information Takeoff definitions associated with it, which become available once a role has been selected. … Roles can be selected from the list of pre-defined roles that Solibri provides, but firms can also create their own roles or modify the pre-defined ones to better suit their workflows and processes."*[144]

Affinity, by Trelligence, allows interoperability between BIM platforms and the programming phase. Trelligence's website reports that as well as possessing *"architectural programming, space planning, and schematic design capabilities, it also integrates bi-directionally with BIM applications like Revit and ArchiCAD, allowing BIM to be extended to the pre-design phase of building projects".* [145]

Affinity allows the compliance of a design programme to be validated in real-time, ensuring that the designer is guided by the client's requirements; it helps avoid manual errors in the transition from programme to design; its interoperability means that the information is modelled only once in the original BIM software; it can generate detailed room data sheets; and it can record and track equipment and furnishing needs.

Neither of these software examples can be personalized through API [146] or development tools, so the resulting work may look constrained. In practice, the range that Solibrì allows makes it possible to create custom rule sets that are useful for many types of analysis.

There are also many other examples of commercial software that can solve specific issues. With "simplebim" software,[147] for instance, it is possible to extract information from the IFC file and from it generate a data sheet in Excel. However, it is not possible to extract the relation between spaces. This relationship, expressed between doors and spaces, does exist in IFC through the parameter "IfcRelSpaceBoundary",[148] but it is not implemented in simplebim.

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[143] http://www.solibri.com/.

[144] Khemlani, 2009.

[145] http://www.trelligence.com.

[146] Application programming interface.

[147] http://www.datacubist.com (last access July 2014).

[148] http://www.buildingsmart-tech.org/ifc/IFC2x4/rc2/html/schema/ifcproductextension/lexical/ifcrelspaceboundary.htm.

VectorWorks includes features implemented for space planning. Using this software it is possible to *"include estimating the area for the spaces, creating an Adjacency Matrix, drawing the spaces on the plan, positioning the spaces, and finally creating the walls"*.[149]

The most recent release from Autodesk considered space compliance for COBie. The "COBie Toolkit for Revit 2015" tool allows designers to verify the prescription of COBie standards automatically.

3.3 Research and independent software

Other research has tried to overcome the issue of correspondence between space programmes and representation through other approaches. The work of Berndt et al.[150] describes a software tool named PROBADO 3D.[151] The authors present a method for efficiently characterizing generic 3D architectural models and converting them into a room-by-room connectivity graph. In this graph, attributed nodes represent rooms, and connections between rooms are represented by attributed edges. With this software it is possible to extract any topological information from any 3D model.

Some other research, although interesting in itself, does not take into account important criteria for architectural quality. For instance, a mathematical method for automated layout distribution is reported in the work of Jankovits et al.[152] The first part of the method determines the position of the departments within the facility, as expressed by a boundary line.

A different approach is taken by the work of Doherty et al.,[153] in which there is an attempt to calculate, through automated tools, the evaluative parameters related to a layout distribution of a hospital, based on the measurement of distances. The authors developed a code in Python that calculates the possible random combination of nurses' paths when they are treating several patients. In order to provide a clear set of results this was not represented as a realistic layout but as an abstraction.

One work has implemented Graph Theory to find out if there is a recurrent scheme of metrics across similar typologies.[154] This proposes establishing the fingerprint of an architectural work in order to understand the recurring characteristics of layout distributions.

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[149] ETHZ, 2009.

[150] Berndt, et al., 2010.

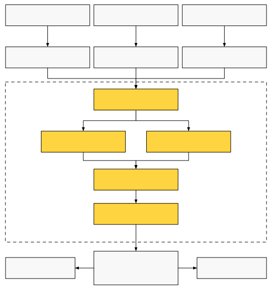
[151] http://www.probado.de/3d.html.

[152] Jankovits et al., 2011.

[153] Doherty et al., 2012.

[154] Langenhanb et al., 2013.

4 Methodology



The main focus of this research is assessing the compatibility of certain functions with an existing building using analytical procedures that consider the best balance between sustainability and optimization of costs and benefits.

When confronting the problem of the parameterization of historical buildings it is possible to refer to a particular kind of design known as “constraint-based design”. This is when the pre-existing building imposes constraints on the design process. In the process of re-design, constraints are expressed by rules that influence the decisions regarding transformation throughout the design process.

An inherent feature of the architectural process is that a design must be performed within a set of given parameters that assist the designer by narrowing the range of possible solutions.

The design approach proposed in this thesis is based on a **case-based research**, subdivided into two main phases:

1) **Theoretical phase**, mainly dedicated to defining the rules and criteria for the evaluation of a design solution;

2) **Practical phase**, which consists in implementing the previously defined criteria and applying them through the use of specific programming languages, the processing of BIM models and the gathering of data.

The theoretical phase aims to define the general criteria and rules for physically modelling the building, the conversion method (using Graph Theory) and the performance, which will be the basis for determining the best design solution.

The practical phase is dedicated to the pure implementation using specific software.[155] Using model checking[156] it is also possible to create rules in an appropriate format and proceed to an automatic assessment of the design solution. Other software can be used to measure the performance of a design solution.[157] All the rules and data were validated using the examples and applied scenarios described in the following sections.

[155] A plug-in was developed for Revit to convert the BIM model into a .csv file, useful for processing this data with MatLAB. All the methods may be easily implemented within stand-alone software and reading the IFC file, for which a Revit plug-in was also developed.

[156] In particular we referred to Solibrì Model Checker.

[157] Such as MatLAB, which can be used to evaluate mathematical considerations.

4.1 The need for standard unification for BIM re-design processes

Following a careful analysis of the literature[158] on the available standards for BIM in the context of existing buildings, in our opinion it is possible to propose some integration for framing interventions on existing buildings.

In this section, with reference to Chapter 2.1 (Standards for existing buildings) we propose a workflow that takes into account the addition of BIM into the building process. The scheme proposed incorporates the directive expressed in ISO 22263:2008 and UNI 11151, integrating the diagram of the main steps with specific BIM models.

The main difference between an intervention on an existing building and a new design project lies in the different access moments in the Life Cycle stages,[159] as depicted in the figure below.

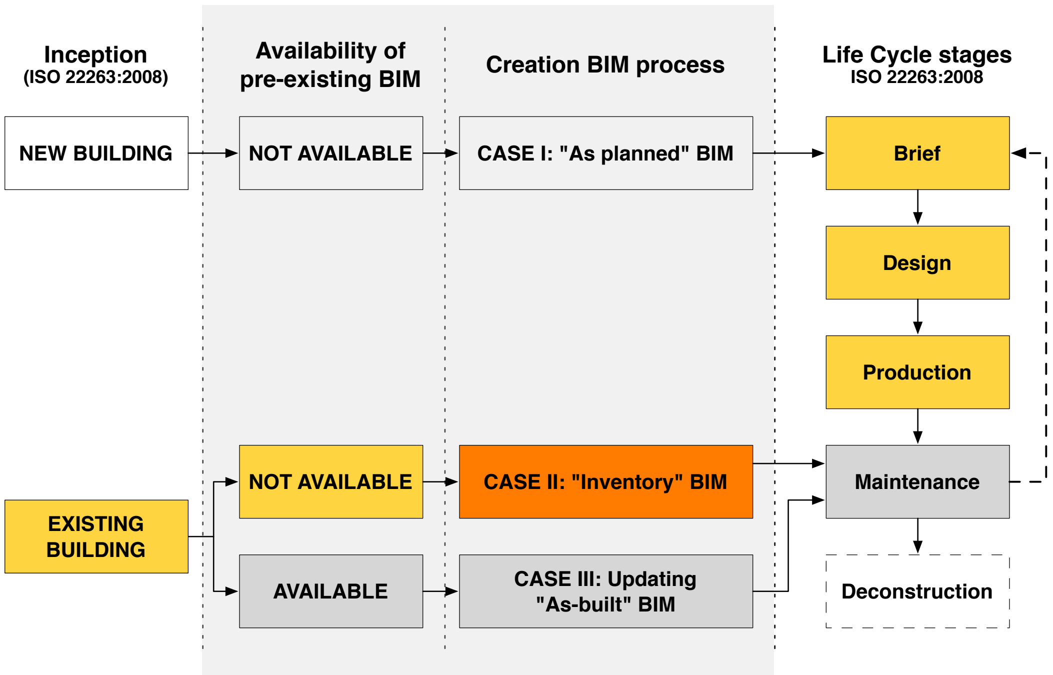


Figure 19 – BIM model creation process [160]

In Figure 19 three different BIM creation cases are shown: case I " As-planned", case II "Inventory" and case III "As-built" BIM.

The first case, "As-planned", refers to the most common process of generating a BIM model. Usually the process starts with a topographical analysis of the design area and then, having analysed the urban law and the prescription given by the government, it is possible to propose a certain volumetry. Using the urban and topographical information

[158] Ref. Chapter 2.1.6.

[159] An explanation can be obtained from the document "Information Delivery Manual: Roadmap" available online at the link: http://iug.buildingsmart.org/resources/abu-dhabi-iug-meeting/IDM_Roadmap_1.pdf (last visited 2 September 2014).

[160] Integrated on the basis of Volk et al., 2014, p. 112.

that may be inserted into a BIM file, it is possible to move directly to the phase of the brief starting with a SG-BIM model, as described in Chapter 2.3.1 – BIM and existing buildings, regarding the level of detail.

On the other hand, as shown in Figure 19, the main difference from the BIM modelling point of view between new and existing buildings is the creation of an "initial situation" (defined in the literature as "Inventory BIM model").[161] Actually the presence in the process of an "As-built" BIM is very rare due to the "youthfulness" and poor implementation of BIM, especially regarding the field of historic buildings.

However, the "inventory" BIM file is the result of a preliminary phase of gathering accurate information that is influenced by the historical sources available and by the type of survey conducted. These two aspects influence the accuracy of the later model during the design and building processes. Inaccuracies in this initial phase can cause errors during construction, adding costs.

By analysing the flow previously depicted, we can confirm that the different approaches towards new buildings and existing buildings have a different "access point" into the flow of the Life Cycle stages. In fact, the process representing the existing buildings flows into a phase that is defined as "maintenance". The process that leads to the final state of a historic building is the result of a series of cycles of transformation from the "brief" phase through the phases of "design" and to the "construction". Observing this process in detail, we can state that the real characteristic of intervention for existing buildings is expressed by a "cyclical loop", depicted in Figure 19 as a dotted arrow.

When the building has a particular historical value, the phase of demolition, intended as the complete removal of the artefacts, cannot exist, as it infringes the principles of heritage conservation issues as defined in art.[162] In some interventions, however, some partial removal of compounds of the building could happen in order to restore it to its original condition.

The updating of a BIM model after the phase of construction, with all the information about the characteristics of the building compounds, is defined as an "As-built" model. This is substantially different from the "inventory" model: while in the first case shown in the flowchart we know the perfect characteristics of the model, and in the second case the inventory, here there is uncertain data due to the approximations of the technicians who have hypostasized about and analysed the building.

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[161] Senatte, 2007; COBIM, 2012.

[162] See Chapter 2.1 – Building heritage.

If we expand the check box “maintenance”, shown in the chart in Figure 19, it is possible to continue the argument by making an additional process to explain in detail the relation between phases of the building process, actors, types of intervention and levels of detail for the BIM models. This is the main reason why we have proposed the diagrams shown in Figure 20 and Figure 21.

The former shows, by analogy with medical terms, the phases of “anamnesis” and “diagnosis” for an existing building, also through a parallelism with the terms identified by the ISO 22263. Just as for a patient, it is necessary to reconstruct the “anamnesis” of the building by reconstructing step by step the most important moments that it has undergone over the years. In this way it is possible to bring out another specialist analysis, the diagnosis phase, which allows us to determine the best type of intervention.

The latter shows how the process influences the BIM models. In this last case, the model will increase the level of information and the level of detail during the process. It is clear that for each phase, several models have to be prepared in order to perform different types of analysis and to manage the information.[163] For each phase it is necessary to use a BIM model with a different LOD.[164]

[163] When we refer to the management of information we often talk about the production of documents or panels for communicating the intention of design. In the future, the paper-based procedure will probably be substituted entirely by electronic devices, but in most of the present cases paper is required.

[164] Ref. Chapter 2.3.1 – BIM and existing buildings.

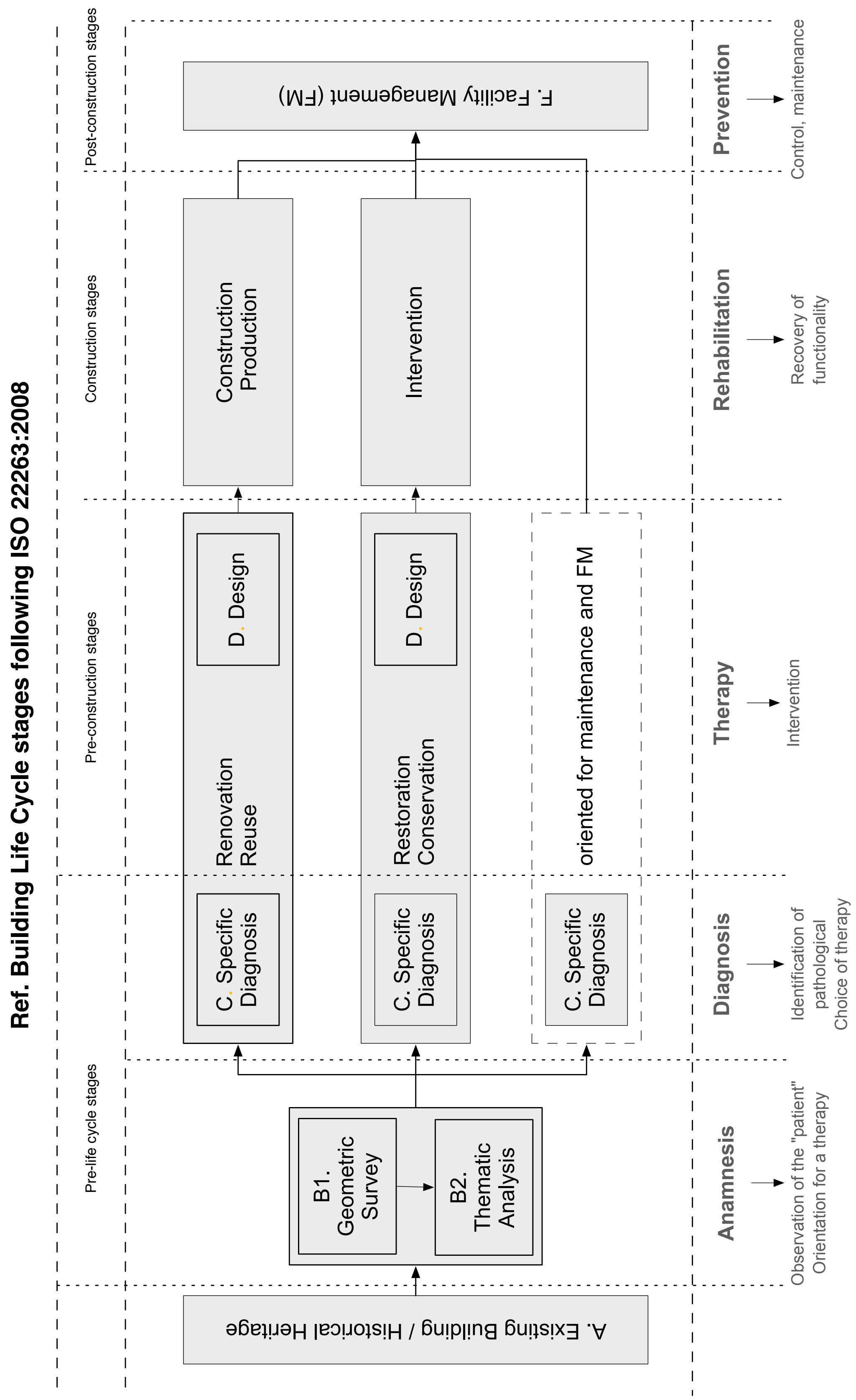

Figure 20 – Building process and types of intervention for existing buildings

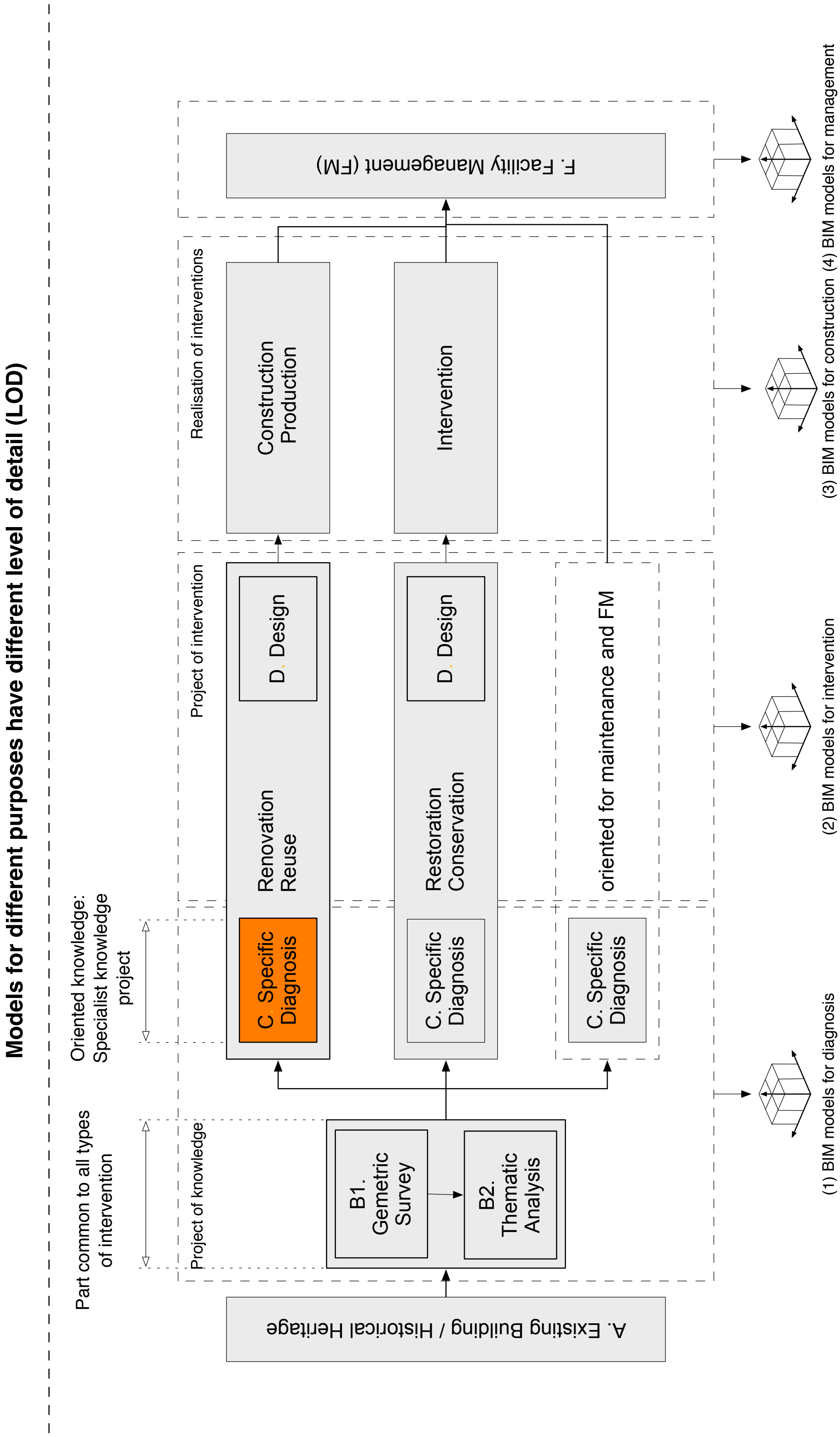

Figure 21 – Creation of BIM models within the life cycle phase

4.2 Proposing a method for evaluating re-design solutions

Assuming the validity of the method proposed for the evaluation of design solutions, shown in Chapter 2.1.5 – Methods for evaluating quality for a re-design project, the method in question provides a numerical value for evaluating a re-design process.

If we consider the whole frame of possible factors to be studied, this thesis will address the topic by proposing a **deterministic approach** through which the best **compatible typological model** is identified from a population of possible cases. Although in design all of these factors, as described by Nuti,[165] are correlated and dependent on each other, the analysis that we will present only takes into account "category B", related to the "dimensional, distributive and functional factors".[166]

Moreover, after a careful analysis of the state of the arts it is possible to say that the method is characterized by few examples of numerical implementation and in general the problem is being addressed by graphical procedures and (to a lesser extent) analytical modes.

Instead, through this research we propose a hybridization of a numerical method of assessment and modern software BIM that permits the comparative study of multiple solutions in a short time.

If we observe in detail the process of assessment, we can highlight three fundamental steps:

1) **Hypothesis of alternative re-design proposals;**[167]
2) **Assessment of compatibilities;**
3) **Selection of the best design solution.**

(1) The first step, the **hypothesis of alternative re-design proposals**, is conditioned not only by programmatic features and political decisions, but also by the typology of the existing building regarding its distributive plan and three-dimensional arrangement.

The typology study may suggest in advance compatible models that will avoid massive intervention within the building. The respect for the structure and the building elements must be design considerations for meeting sustainability criteria. In this sense, the typology can represent a set of constraints that must be respected. There are different basic characteristics for highlighting the typological model, which are often related to

[165] Nuti & Campolongo, 1989.

[166] Ref. page 22.

[167] Could be considered also if there is a change of function or not.

geometrical features. For instance, the floor plan can be characterized as a linear, central or radial type. The particular historical period to which a building belongs also provides important information. In accordance with a particular spatial program, the choice of a new typological model has to respect the starting typology.

(2) The **assessment of compatibilities** is an evaluative phase that consists of comparing the pre-existing building with the typological models proposed. This assessment of compatibilities aims to analyse the degree of correspondence with the original existing building, and must take into account: (a) the condition of existing elements and the status of conservation of the building's component technology (based on its compliance with the required technological performance needed for the structure's new functions); and (b) evaluation of the degree of correspondence of the measurements with those of the new function (deriving from compliance with standards and the law, dimensions, geometry, ratio of windows to floor area, maximum load, orientation, etc.).

This second point in particular is the object of our study. Although there was a general approach regarding the assessment of functionality, we will study and implement in detail the criteria of "redefining internal and external mobility and accessibility systems" that was defined in section 2.1.5 – Methods for evaluating quality for a re-design project – Rule of transformability – 4. This rule of transformability essentially considers two main aspects of the pre-existing building, the **structural arrangement** and the **distributive organization**. It is believed that these two elements characterize the further path of building modification, and therefore define the constraints and potential. Although the two aspects are correlated, the first aspect will not be considered in the subsequent research.[168] It is still obvious that a structural consideration goes into the typological assessment of the pre-existence. Regarding the distributive organization, even if it is related to functional considerations, it is possible to ensure the quality of the distribution by realizing the following **objectives**: (i) congruence of distribution of axes and (ii) no blind rooms in the connection zones. The first objective is justified by the correctness of an organizational scheme for the paths (the connection between two remote spaces within the building must be continuous, without any interruption). The second objective aims to reduce to a minimum those spaces that do not have a direct connection with the outdoors, including those areas of connection that take advantage of what could be a better use of interior space.

For the evaluation we have developed a method that is based on the realization of a BIM model used to analyse different design solutions. The model will be processed

[168] Although it is possible to make some consideration.

through software that allows the user to extract data. Moreover, the decision on the best design solution relies on measurement of the “**performance”**, which represents a set of values[169] applicable to a specific field of investigation.[170] In general the solution that shows a better level of performance will be considered for further investigation. Part of the study has been dedicated to gathering information so as to achieve a correlation between parameters and the physics of architecture (defining the metrics to evaluate a “good” or a “not good” solution).

(3) Selecting the best design solution may involve an evaluation of both performance and aesthetic criteria. Next, the chosen design can be refined to create the best result and approach the final design solution. Once the process is exhausted, the best design model solution in relation to the relevant factors is created. For a solution to be chosen, all the evaluative values have to be positive with regard to both the numerical analysis and the qualitative assessment.

Before going into detail about the main features of the thesis it is important to highlight some considerations regarding the limit of applicability.

The method is based on consideration of a small number criteria: it does not take into account all the complex systems of evaluation in designs. Usually modalities of evaluation can be diversified into functions of quantifiable qualities and non-quantifiable qualities. In the first group we can list evaluations for structural, energetic and acoustic factors; in the second group, we can list human factors such as perception, aesthetics, ergonomics, impact on social systems, interpreted meaning and so on.

Moreover, it is not a given that a good solution highlighted through a mathematical approach will coincide with the best architectural solution. The major shortcoming in this process is that it does not preserve the perceptual aesthetic criteria in the design solution, which must necessarily come under human control.

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[169] Achieved from the Graph Theory – ref. Appendix B.

[170] This thesis will present a method of evaluating design solutions for circulation problems with measures and indexes established by graph theory. The same method can be applied to many other types of analysis that take into account multi-criteria evaluations (sustainability, economics, construction, etc.).

Type of analysis for the evaluation process

The type of analysis used for the evaluation process is based on two main aspects:

- Assessment of **functional compatibilities** **(ref. Chapter 4.5.1);**
- Assessment of **distributive layout** **(ref. Chapter 4.5.2).**

The first assessment consists of a preliminary analysis of the inventory file, giving rise to a critique of the pre-existing building, and then comparison of this with the compatible typological models chosen by the designer, according to the following steps:

1) Individuation of the relationships between spaces, highlighting the activities connected to them and generating the graph for the inventory model;
2) Individuation of dimensional factors expressed by width, length, height, volume and area for each space;
3) Individuation of hygiene factors expressed as a ratio of glass to gross floor area for each space;
4) Individuation of structural safety expressed as maximum load function for each space;
5) Assessment of the coherence of a distributive path, based on the measurement of the indexes and parameters at the graph level.

All these points can be analysed using commercial software that permits the compilation of rules for an automated assessment.

The second case, however, requires the use of Graph Theory and the implementation of custom software that permits interoperability between the BIM model and mathematical software. This assessment will be described in more detail in the chapters related to the implementation.

4.2.1 Assessment of **functional compatibilities**

A change in building function must be verified not only through dimensional criteria but also through a series of standards and legal compliances: hygiene rules, structural behaviour, health standards, security measures and laws specific to the particular building typology (for instance, in a hospital, disease treatment, etc.).

The functional compatibilities can be verified by making a direct comparison of **databases**.[171] Each spatial group and in particular each space can be described by its intrinsic and extrinsic features. A database can contain all the data necessary for comparing activity and function. These data are created manually according to a minimum/maximum range. Some values to consider during the assessment are as follows:

a) Dimension;

b) Gross surface area;

c) Volume;

d) Glass/floor area ratio;

e) Number of occupants;

f) Number of workers within the space (permanent position or temporary position).

The process of assessment follows the workflow depicted in Figure 22.

The first step is the analysis of the pre-existing building. Each space is characterized by many parameters (as shown in Figure 22.1, a generic space has dimensional and performance features). All these parameters are collected into an internal database that can also store structural and energy requirements (for instance, the maximum load acceptable and the energy behaviour required).

It is then possible to hypothesize several new functions (Figure 22.2). For each function chosen, a database has to be complied that contains information regarding each specific function (for instance, for a conference hall it is necessary to define dimension, area, volume, fire ratio, and so on). This phase requires an in-depth study of manuals and the regulations,[172] as well as the collection of case studies. At the moment, there are few examples of sharable BIM databases that describe space performance.[173]

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[171] BIM models already have a database implemented but the procedure can also be performed with a simple Excel spreadsheet.

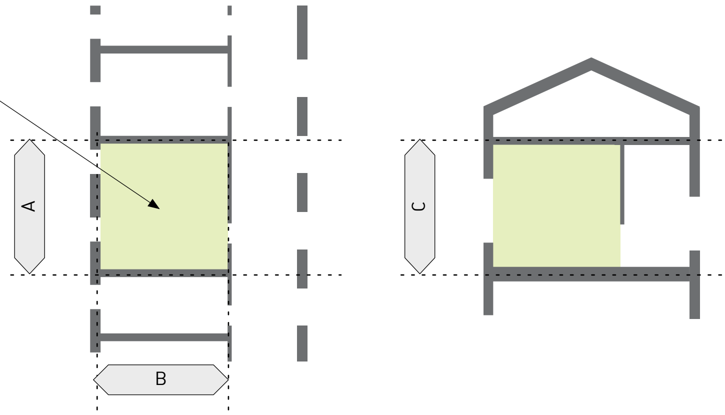
[172] For instance the manual written by Neufert.

[173] Some research has been developed in the medical field.

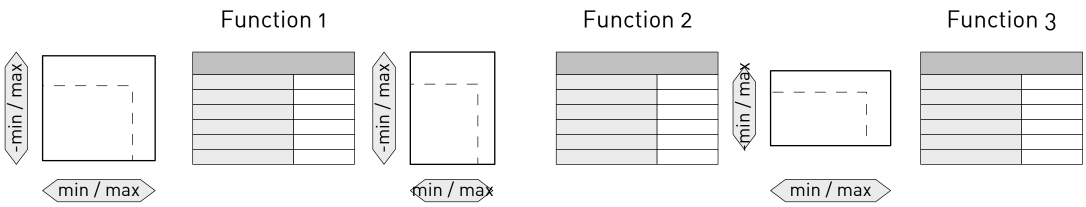
The comparison is performed by comparing the data for the starting situation (the pre-existence) with the new, hypothesized function. This demonstrates the degree of compatibility for the new function, expressed as a percentage of fitting (Figure 22.3) for each space.

1. Initial situation

ID: SPACE 01	
Original function	Room
A	value 1
B	value 2
C	value 3
Surface (S)	value 4
Volume (V)	...
Surf. Windows (W)	...
Ratio W/S	...
Maximum Load	...
Exposition	...
Daylight	...



2. Possible change of function



3. Evaluation of compatibility

ID: SPACE 01	
Original function	Room
A	value 1
B	value 2
C	vale 3
Surface (S)	...
Volume (V)	...
Surf. Windows (W)	...
Ratio W/S	...
Maximum Load	...
Exposition	...
Daylight	...

Evaluation of function compatibility					
function 1		function 2		fucntion 3	
range 1	85 %	range 1	15 %	6,50 m	95 %
range 2	50 %	range 2	15 %	7,80 m	92 %
range 3	30 %	range 3	10 %	4,50 m	90 %
...	...	...	...	...	...
...	...	...	...	...	...
...	...	...	...	...	...
range n		range n		range n	

Figure 22 – Assessment of functional compatibility

The evaluative process then goes on to a subsequent step. The process shown up until this point allows the designer to propose a new compatible function, but this is still subject to the decision of the owner, who may be a private or public entity. Hypothesizing that we have defined a function, it is possible to start with the phase of design and assembling a matrix of relation.

A relationship matrix (or adjacency matrix)[174] is a planning tool that enables the systematic evaluation of relationships between areas and spaces within a building. The designer assigns a value to a spatial relationship on the basis of a five-point scale: close proximity essential, close proximity desirable, separation desirable, high separation desirable, and no spatial relation. The appropriate adjacency relationship is then indicated in each box formed by the intersection of two spaces (Figure 23).

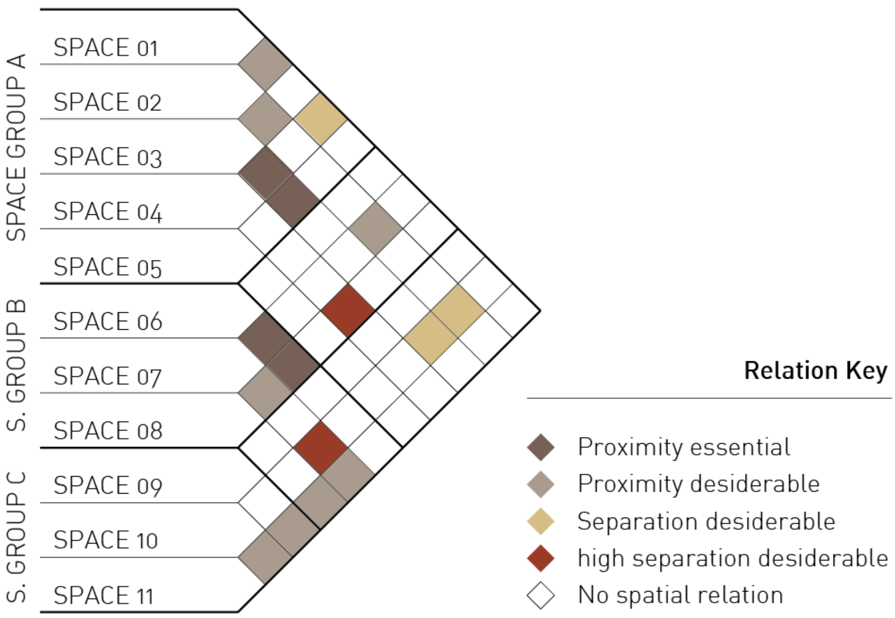


Figure 23 – Example of a relationship matrix

The matrix is reviewed for its critical relationships and represented graphically through a diagram created to illustrate these relationships spatially. In addition, the "mathematical relation" (adjacency) can be represented in a graphical form through a diagram like that shown in Figure 24.

[174] In general the terms can be used as synonyms, but in the context of this thesis it was decided to separate them with two meanings: the "relationship matrix" sets links between spaces without giving a numerical value; on the other hand, the "adjacency matrix" assigns a value to a specific link.

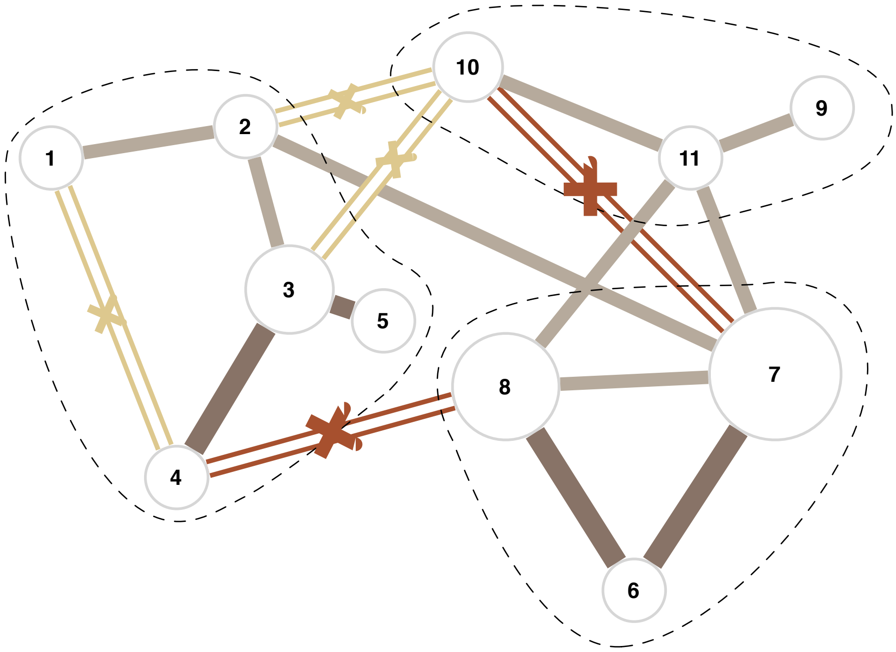


Figure 24 – Representation of the mathematical relation

Through this method it is possible to study different issues related to the design problem. It is possible to represent the geographical exposition of spaces, access to daylight or different types of users. In this last category, for instance, it is possible to separate different types of flow within the building, by subdividing it into public or private users, suppliers, workers, hazardous materials, and so on. Through the graphical overlapping of all of these, it is possible to highlight design criticisms and intervene in the decision-making process to achieve a better design solution.

4.2.2 Assessment of **distributive layout**

New usage requirements can induce changes in the structure of the paths related to the type of users or materials that have to be transported within the building. Materials and users may be considered as flows within the building. Intersections or overlaps between them have to be verified in order to avoid clashes.

The requirements can range from simple improvements to connections between individual compartments within a functional unit (opening/closing of doors, construction/demolition of partitions, etc.), up to a complete revision of the distribution and organization of functions. The following is a list of recurring situations:

1) **Fragmentation of the internal spaces** – in some contexts it is possible to subdivide the space both horizontally and vertically in connection with the progressive specialization of functional spaces. After a fragmentation it is necessary to check the hygiene criteria related to the ratio between windows and floor area.

2) **Changing axis distribution** – paths are one of the most complex issues in specialist buildings, as they have to respond to multiple demands that are often in conflict with each other. Interference between paths has to be highlighted and resolved; one possible tool for this is Graph Theory.

3) **Introduction of vertical or horizontal connections** – the introduction of electro-mechanical systems is an element in the rationalization and efficiency of distribution patterns.

4.3 Defining the model for the functional organization

The most significant information for evaluating the functional behaviour of the building with the aim of defining the optimal functional layout concerns **spatial organization** and **internal circulation**. In defining the former, we can refer to the definition of "activity" given by Tabor.[175] He states, although it may seem tautological, that *"an activity is something that occupies a location"* and more precisely, an *"activity is an organizational element, a location is a constructed element".* Spatial organization means resolving, in an optimal manner, a number of activities within an equal number of locations.[176]

For the latter term, circulation is the primary organizational element of any architectural structure: we experience a space in relation to where we have been and where we anticipate going. A clear circulation system is often considered an element that positively affects the perception of the form and spaces of a building. The two previously mentioned methods of analysis use abstract representations to highlight the problems and potentials of a layout distribution. To trigger this process we can refer to Graph Theory, which makes it it possible to decode functional relation schemes in order to structure the information.

The process of converting any layout into a graph can be defined as "**dissection**". In medical terms, this means "to cut open and examine the structure of a body". In the present sense, architectural dissection is the process of decomposing an elementary part of a building in order to understand how it functions.

As mentioned in the state of the arts and in the literature review, the process of abstraction of the architectural layout is well documented.[177] Useful data can be acquired by applying Graph Theory. As mentioned, a graph is an abstract representation that is often denoted by an ordered pair G = (v, e) where v is the set of vertices or nodes and e is the set of edges. Reciprocal relations of exchange connect all of these nodes (Figure 25).

[175] Tabor, 1976, p. 290.

[176] Scarano & Piemontese, 1997, p. 29.

[177] Ref. Chapter 2.2 – Conceptual design.

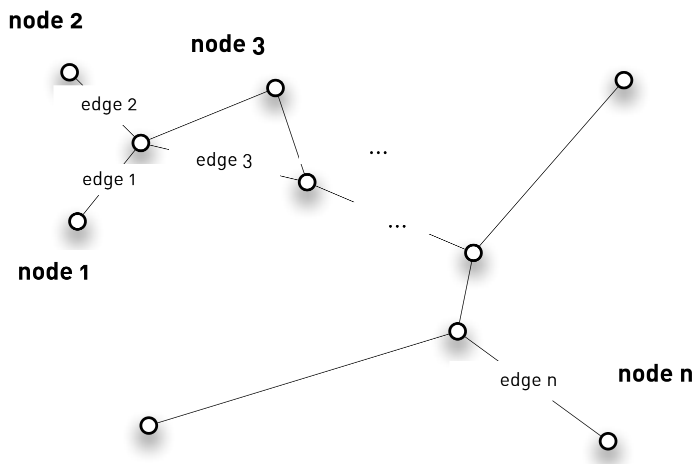


Figure 25 – Example of a generic graph

A vertex represents a specific space within a layout distribution, and an edge represents the relationships established between these spaces. This method of abstracting and converting any layout distribution into a graph has to follow precise rules for assembling the graph. As described by Scarano and Piemontese,[178] we can start by defining two different types of node with different hierarchical levels:

A – spatial unit nodes, which are located at the geometrical barycentre of the boundary of the space. When the unit does not coincide with a simple geometric figure it is necessary to decompose the shape into more elementary figures (see Figure 26), find the related barycentre and subsequently, using the geometry of the masses, determine the barycentre of the overall figure;

B – transit node, which coincides with the points where changes of direction occur, during navigation within the building.

Figure 26 shows an example of the identification of spaces. In the subsequent work, we will also use a colour convention for identifying macro categories of space, subdivided into: generic spaces (yellow), circulation spaces (red), service spaces (blue), transition nodes (white) and entrances (black).

[178] Scarano & Piemontese, 1997, p. 42.

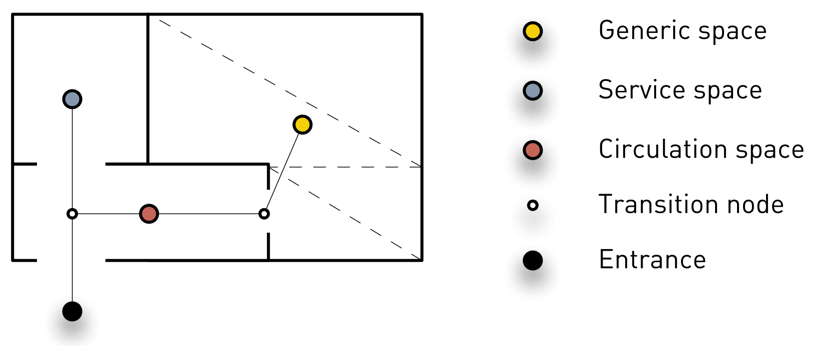


Figure 26 – Spatial unit node and transit node

If a space has more than one activity, the node can be expressed by a group of nodes. In existing buildings, in fact, single spaces often include multiple activities. We can take three different cases into account:

a) **Adjacent activity**, having a direct connection; the distance in this case is calculated as the sum of the distances from the transition point;

b) **Activities connected through a single circulation space**: movement between activities cannot cross any nodes of circulation but can cross single nodes. In the first case, the distance will be calculated by simply adding the distances from the barycentre of the space activities to their respective entrances, and, in the second case, adding the distance between them to the distances from the nearest node of movement;

c) **Activities connected through a chain of spaces**: the distances from the entrance of the activity must be calculated and added to the summation of the connections, which, starting from one of the two, can reach the other crossing the smallest possible number of nodes.

The resulting graph may have **cycles** that represent alternative routes. Assuming that the paths are the shortest routes of circulation, it is necessary to define how to identify, among all the possible combinations of paths, those that create the minimum distances.

Depending on the type of function, the spaces are linked to each other by types of association and connection. In Koenig's dossier[179] the nature and the types of connection are defined, revealing few clear cases: *"The junction between spaces doesn't denote a membrane, but only shows that between two spaces a certain relationship of communication exists that can be: (a) physical, (b) visual and (c) sonorous"*.[180] In general,

[179] Koenig, 1962.

[180] Koenig, 1962, p. 19.

different types of partition may inhibit some of these communications. For instance, an opaque door can inhibit (a), (b) and (c); a glass door (a) and (c); a curtain only (b); and so on.

This means of classification provides important information on how to assemble the graph, but it does not explain how to represent the behaviour of a hypothetical user within the building.

The proposal extends the classification to take into consideration horizontal and vertical connections, which are subdivided into: (1) openings, (2) doors, (3) ramps, (4) stairs and (5) elevators.

For all of these categories it is possible to define a value (a distance or a parameter) for the junction that represents how it enables a transition between one space and another. This is an important topic, especially when defining accessible circulation paths and or when guaranteeing wheelchair accessibility. For instance, we can give a higher value to stairs than to elevators, as well as for doors in comparison to openings.

Every space belongs on a particular vertical level. There are cases where the space has a particular configuration, known as “double volume”. This refers to an architectural space whose height is double the normally considered space. It is usually possible from a middle level within a double volume to see the level below. In this case, the resulting space may be decomposed into multiple volumes that are topologically connected to the touch operator. In reality, when assembling the graph, we do not consider connections between the middle and bottom levels because we are only considering issues of circulation. The connection between these two spaces needs to be evaluated only if a vertical connection is present; otherwise the two spaces belong to two different levels.

4.4 Defining the behaviour model

The tool that we will describe is an aid-tool for design that makes it possible to compare different design solutions. Usually an "algorithmic" method is used to detect the "optimal" solution, according to a series of parameters. In our opinion, due to the highly subjective nature of the results in architecture and to the number of parameters to be taken into account, a mathematical method is reductive. One possible method may be decompose the design problem into several sub-issues. Moreover, assuming as valid the principle of superposition, the solution may be identified through the evaluation of quantitative or qualitative parameters.

Graph Theory helps to solve this task: it is possible to calculate quantitative values for several graphs representing several design solutions. Each of these graphs has specific features that are described by parameters. In some cases high parameters represent a better-connected graph, in other cases a low level of the parameter represents the worst condition. However, these values are a warning about driving the decision-making process on the basis of an evaluation of the network.[181]

In some design contexts the issue of circulation problems predominates. In fact one criterion of design may be to consider movement within the building as several types of flow. For instance, we can consider the flow of **users** and **materials**. Drawing several graphs subdivided by types of flow and overlaying them can highlight points of conflict that have to be studied in detail in order to minimize **interference**.

This is the typical issue when designing a hospital or an airport: in fact, here the main aspect of design is to consider the flows of users – "emergency intervention" and "patients" in the hospital, or "security control" and "travellers" in the airport (for instance) – that have to be considered separately. Some of these flows have to be minimized in terms of movement, others should not intersect other paths, while others may not have access to specific places.

For this purpose, it is necessary to define a set of procedures for a **behaviour model** that satisfies the specific objectives (decided by the designer in the context), with the aim of defining a two-dimensional or three-dimensional layout distribution.

Starting from this premise, the final stage of the design process is to create an optimal distribution of functions in relation to the previously defined variables. It is essential to identify which of these variables can be quantized and calculated.

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[181] The data are described in Appendix B.

Before describing in detail the practical method for identifying spaces and relationships between activities, it is necessary to define what is meant in this work by "**optimal**" as the term will be used later in the text.

Explaining what is meant by "optimal" is not trivial and the term must be defined holistically. Many researchers agree that the optimal solution in terms of internal circulation is the one that is the most efficient. This means that in order to increase overall efficiency it is essential to define the aggregation between activities in a way that minimizes the **total movement** that occurs within the building. However, how an aggregation is realized is closely related to the criteria chosen for the quantization of circulation and, consequently, to the cost of association between activities. Two activities can be defined as "associated" if there is a considerable number of movements (of people, objects, materials, air, energy, etc.) between them.

The total movement – defined in Graph Theory as the "cost of the graph" – can be thought of as the function that must be minimized. The cost, if we think of two activities i and j, can be represented in the first analysis as the distance between activities.

One criterion for choosing between possible paths may be to minimize the total number of movements of a hypothetical user. Crossing a node, which we have described above as the point where a path changes direction or intersects with another path, is clearly a "loss of time" and quantifiable in relation to the number of intersections.

It is now possible to extend the analysis by considering the time necessary to cover the distance between i and j, or by associating a user cost in relation to the activity (for instance, for a healthcare company it is essential to minimize the movement of doctors rather than visitors for obvious cost reasons).

First of all, it is necessary to explain the process of calculation used in an analytic and pragmatic approach. The method may consider a starting node (usually the entrance but possibly also a generic node) from which is developed a tree graph that shows all the possible paths from the starting node. This process of transformation from a generic graph into a tree graph consists of creating a directional/oriented graph in which the routes are determined (only one possible route may exist from one activity to another).

In addition to the graphic procedures described above, it is possible to use a **mathematical method**: the Shimbel value can be used to determine the shortest path within a network of movement.[182] The method uses a dispersion matrix and does not directly identify the shortest path, but rather its length. In this way the lowest values of the paths between each pair of activities is created. The aim is not, in fact, to visually identify

[182] Rodrigue & Ducruet, 2013.

what is the fastest path, but to build a matrix of associations between the activities related to the particular spatial organization that is being analysed. The parameters that we will account for in the continuation of the work are described in detail in Appendix B.

4.4.1 Measuring the performance

Several measures and indices can be calculated and analysed in Graph Theory in order to measure efficiency. Many of them can be used to:

- Express the relationship between values and the graph level;
- Compare different graphs in a specific situation.

Some parameters are necessary in order to describe the size of the graph by its number of nodes and edges. With regard to the total length and traffic, several measurements are also used to define the graph's structural attributes: the **diameter**, the **number of cycles** and the **order of a node**. The indices of a graph provide numerical criteria by which to evaluate one graph against another, in order to determine which is the most efficient. Some indices use spatial features (distance, surface) while others use the activity level (for instance, the traffic between nodes); still others give only topological information about dimensions.[183]

The next phase deals with the relationship between the internal and the external. It is necessary to highlight everything that flows between the external system (environment) and the building, whether of a physical (objects or people) or informational nature (such as visual flow or generic information).

The **access graph** is fundamental to evaluating the relationships of distance and circulation difficulty: every element can be organized into a graph that shows its relationships to other locations and the access/exit point of the structure. An access graph is an oriented graph that connects each movement from the entrance to remote nodes. The figure below gives an example of an access graph.

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[183] For a definition of the measurements and indexes see Appendix A.

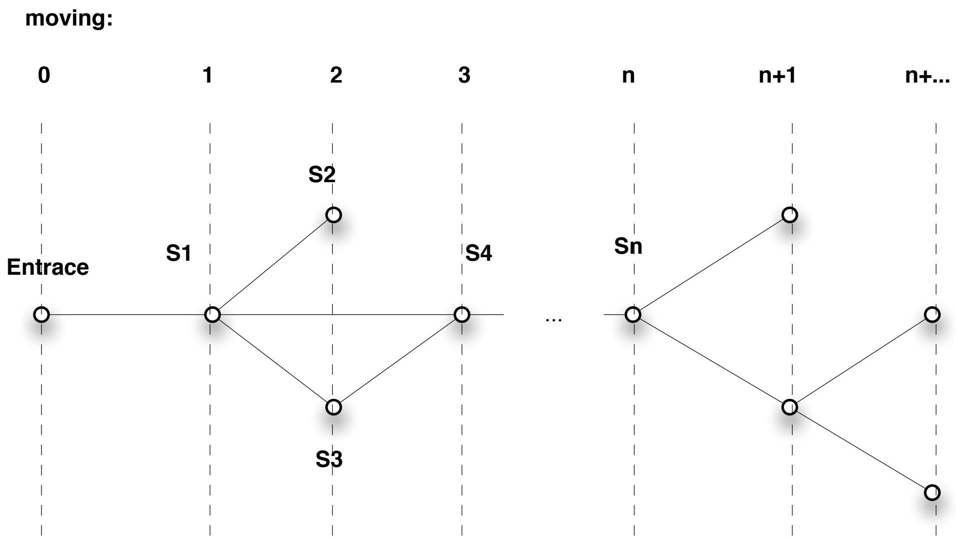


Figure 27 – Example of an access graph

This particular graph has to be organized for access levels, in order to make it easy to compare the different configurations of a spatial layout and elaborate them for all access points. This graph, the **access graph**, can be considered a sub-type of **adjacency graph**.

To evaluate the percentage of adjacencies actually used for direct connections, it may be useful to compare their average values with the access graphs of adjacency graphs.

Furthermore, it is possible to separate the different user paths and overlay the different graphs. With this method it is possible to highlight the **critical nodes** that have to be analysed in detail, in order to understand if there might be other solutions for circulation.

4.4.2 Example of performance calculation

To make more explicit the theory that we have so far introduced, we can refer to the following case study. The project is the Mrs. Thomas H. Gale House, designed by Frank Lloyd Wright (Figure 28).

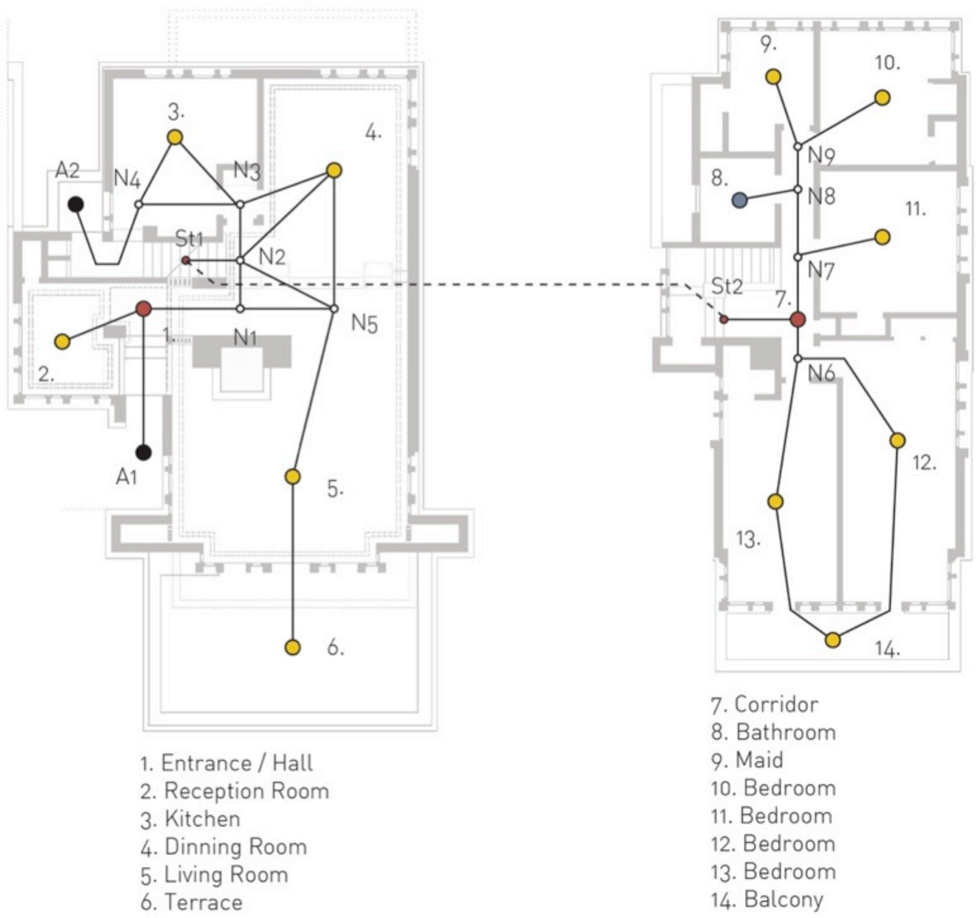


Figure 28 – Graph of Mrs Thomas H. Gale House

The red, blue and black nodes represent the following spatial unit nodes: functions, services, access. The white nodes represent transit nodes.

The first step seeks to identify the **support structure** (1). All the barycentres are determined through a simple operation, thanks to the regularity of the geometrical figures that enclose each activity. Only with the kitchen is it necessary to consider the space as the sum of two rectangular shapes. In determining the barycentre of this particular shape, it is necessary to use funicular polygons, as shown in Figure 29.

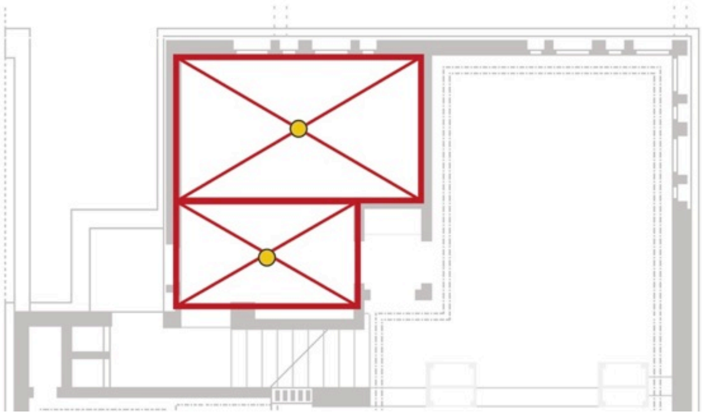


Figure 29 – Calculating the barycentre for a complex space

The support structure is then transferred onto a graph, whose vertices represent the nodes and whose junctions are converted into edges with a certain weight.

It is not necessary for the values to correspond strictly to the real values; the important and relevant results are respected and we can then refer to any scale of value without altering the result of the analysis. In fact, in order to make the information comparable with other related case studies, the data will be subsequently parameterized according to a scale of values (for instance, distances from 1 to 3 meters are parameter “1”, distances from 3 to 8 meters are value “2”, 8 to 15 are value “3” and so on).

Applying the graphic procedure involves repeating the process n times, where n is the number of activities within the structure. The process is therefore quite long and laborious, so here we aim to find only the shortest paths from the entrance to all other points.

A sub-graph is constructed, starting from the entrance, with successive additions of activity, each considering only the connection that can bring it to the next node. Whenever a cycle is detected within the sub-graph, it is essential to check whether there is some indirect path that is shorter than the direct one. In the example, in which all other alternative routes are indicated with dashed lines, this never occurs.

As already mentioned, the graphical process needs to be repeated n times in order to obtain all the information required to construct the relationship matrix of the activities. This can be achieved quickly using a method based on a dispersion matrix. The operations on the matrix S, expressing the original graph, are in fact much simpler than might appear from the mathematical formulation of the process.

If we look at the case study under consideration, the exponent of the matrix is equal to 6. This shows that all movements from one activity to another are possible in a maximum number of six steps (ie going through at least five nodes, excluding the source and destination).

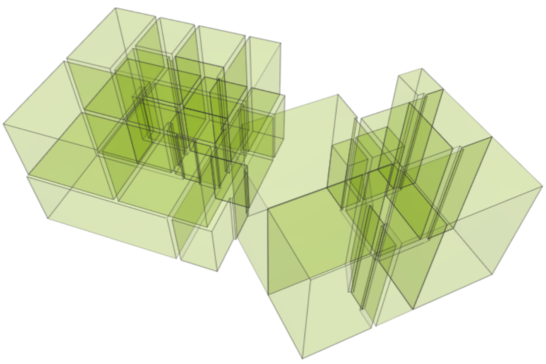
The relationship between pairs of activities, excluding consideration of the path length, must also be assessed in relation to the number of nodes of movement present in the graph.

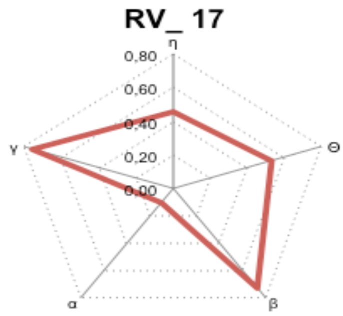
In fact, between two paths of equal distance it is necessary to consider as better that which has a smaller number of nodes to cross. This requires a further matrix, named an interference matrix, and its corresponding graph evaluates the degree of relationships between activities on the basis of the parameter of scale.

4.4.3 Displaying performance and evaluation

The final step is to display the result and communicate the information to the design team. The performance represents the sum of the results of the analysis and it is a summary of the comparative evaluations. The panel that can be used to communicate data may take a form like that shown in Figure 30. The spider diagram shows a syntactical representation of the value calculated on the graph.[184]

Input								Feature of the graph			Performance					Cost in movement	
Value:																	
v	e	A	V	L(g)	PE	p	u	d	g_d	l_g	η	Θ	β	α	γ	C_{tot}	MST
(space)	(edges)	(surface)	(volume)	(total leght)	(people)	(sub-cycle)	(cycle)	(diameter)	(density)	(av. leght)						(total cost)	(cost)
25	25	356	850	12	8	0	0	11	0,083	4,73	0,48	0,32	1,00	0,00	0,36	32,0	29,0





IFC file – X-ray view of the spaces	**Performance**

Figure 30 – Example of a panel to communicate the value of performance

Starting with input values that are composed of the number of nodes (v) and edges (e), the total area (A) of the building and the volume (V), the diagonal or diameter of extension expressed in meters (Lg), the number of sub-cycles (p) and cycles (u), it is possible to calculate the dimensionless parameters that express the performance (η, Θ, β, α and γ). The feature of the graph is achieved with specialized software (Gelphi) and the cost in terms of movement is calculated using MatLAB.

[184] Details and descriptions of parameters are given in Appendix B.

The evaluation consists of comparing the parameters achieved from the analyses of a population of possible design solutions. Depending on the type of objective that we want to pursue, it will be decided which parameters have to be maximized, minimized or guaranteed by a certain average.

If we hypothesize that the objective is to find the most efficient layout distribution for an airport, for instance, one criterion would probably be to minimize the number of movements and avoid overlapping between several flows. This principle could be extended to the flow with the building and to the vehicles distributed around the landing and parking areas.

In general this is a common problem, in which we have to consider the:

- **Cost minimization**: a good path should reduce the overall costs of the transport system. This implies construction as well as operating costs;
- **Efficiency maximization**: efficiency in a graph is expressed in terms of a reduction of interference between several activities. This may also be realized graphically, overlapping several paths.

Choosing a solution is thus a compromise between the cost of a graph and its efficiency, but we also have to consider the solution's coherence with the architectural criteria.

4.5 Implementing the process through the software

All the theory proposed in the early part of the chapter may be partially implemented using commercial software. This was the main reason for developing a plug-in that can overcome the difficulties of the present situation.

As described at the beginning of the chapter, the pre-existing building must be modelled according to a certain level of detail, as well as with information from a P-BIM. For our purposes we downgraded this into a conceptual model and extracted from it an SG-BIM and S-BIM. For our experiment the S-BIM level for every model was guaranteed.

Since the aim of this procedure was to define compatible models for a pre-existing building, it is possible to create a framework that shows the types of assessments in relation to the software used. (Table 3).

Table 3 – Type of assessment and tools

Type of assessment	Tools
1. Assessment of functional compatibilities	Solibri Model Checker, Graph Theory, Excel
2. Assessment of coherence of distributive paths	**Plug-in for Revit**, Graph Theory, MatLAB

It is possible to partially define a compatible model that respects the pre-existing building using commercial software (as described in Chapter 3). Other analyses must be performed using custom software that allows information from a BIM model to be extracted and enables interoperability with MatLAB. The present research traces a possible implementation for a standalone software program that could operate independently of commercial software.

Some rules may be implemented though the use of Solibrì; others need custom tools to be programmed that allow the necessary information and relationships between spaces to be extracted from the BIM model.

In general the approach is subdivided into two main parts:

- Analysis implemented through Solibrì Model Checker (section 4.7.1);
- Analysis implemented through MatLAB (section 4.7.2).

4.5.1 Rules with **Solibrì Model Checker**

Rules are the core of Solibrì Model Checker its model checking. This software can be used to compare two IFC models, one representing the pre-existing building and the second representing the re-design solution.

A rule, coded in an appropriate language, can check a model according to a single aspect (eg duplicate walls are not allowed) or from some specific point of view (eg use of correct construction types). Some rules also show a key characteristic (eg list of window types and sizes) of a building.

Rules are parametric, which means that you can control their behaviour by setting the parameter values. This makes the system extremely flexible; rules can be configured to check, for example, project specific issues. It is important to understand that the rules do not change the model; they only find potential problems. It is always up to the user to decide which issues are important and what actions to take.[185]

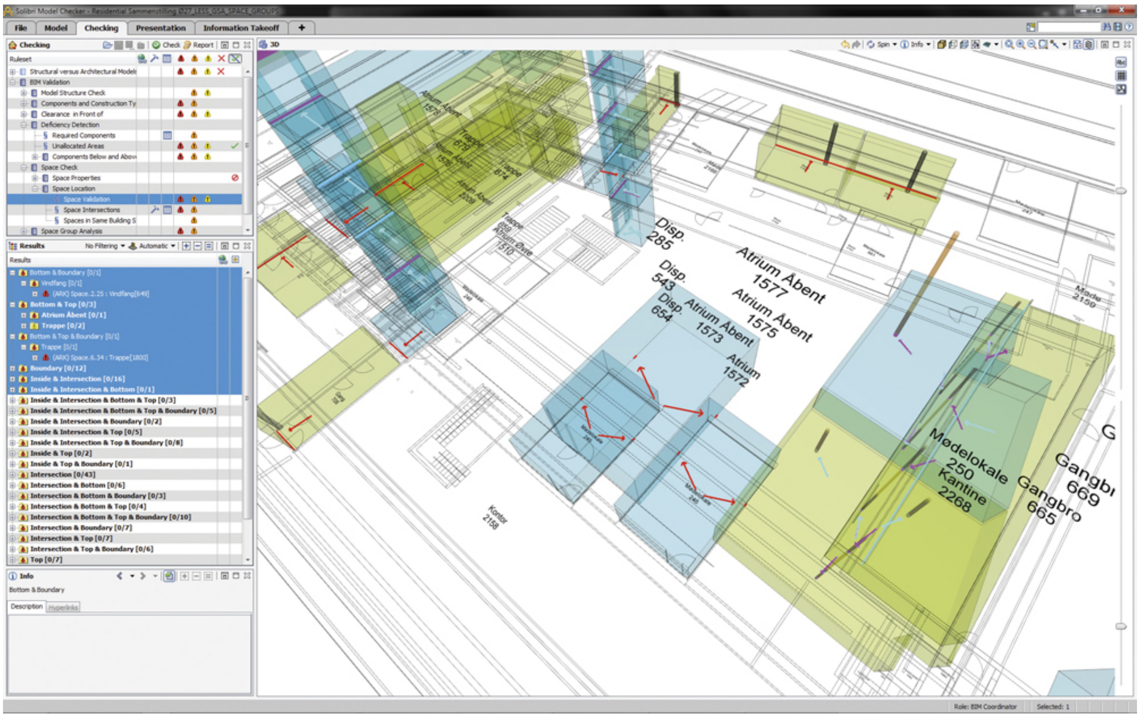


Figure 31 – Example of room validation and clash detection though Solibrì [186]

[185] Solibrì Model Checker, 2014.

[186] http://www.archimag.org/wp-content/uploads/2012/01/Solibri_Screen_Shot_Space_Validation_Checking_Results_01.jpg.

Using Solibrì it is possible to assess the following sets of rules. The main categories of "Architectural checking" include:

- General space check and advanced space check;
- Structure versus architecture;
- Space programme;
- Model revision comparison.

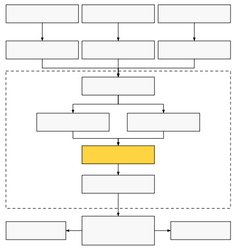
The first sets of rules, "General space check" and "Advanced space check", essentially check the consistency of the models: the software controls whether the spaces within a model are labelled and have a door or connection. There is also a control named "space dimensions must be within sensible bounds" that controls whether the space has a certain height (> 2,00 m) and a certain area (> 1m^2). The advanced space check includes important rules such as "Space must have enough window area". This hygienic rule is expressed as a percentage range that depends on the national regulation (for instance for Italian law the minimum required is 12.5% (1/8) of the gross area of the space for rooms and offices, smaller ratios are available for storage and other functions).

The second set of rules, "Structure versus architecture", and especially the rule "Doors and windows should not intersect with structural components in the structural models", checks the consistency between the structural model and the architectural model.

The third category, the "Space programme", is one of the most important rules because it is strictly related to the design phase, rather than related only to checking the consistency of the models, like the above-mentioned criteria. With this set of rules it is possible to establish a range of functional areas within a particular space to a certain tolerance, or to count the spaces created by the programme, or to calculate and verify the distances between spaces according to given requirements.

The last category, the "model revision comparison", is the final check and is performed as a comparison between the inventory model and the various new design proposals. Solibrì gives information about the elements that are added, removed and modified. With this analysis it is possible to understand what elements are invasive and which fit into the pre-existing building with the least intervention.

4.5.2 The **plug-in** for extracting information



For complex buildings, calculating the network performance may be a useful way to evaluate between the generic and the particular design problem, and assess which graph is more efficient in terms of connections and exchanges within the building.

There is no commercial software for calculating the measurements and the indices for a graph starting from a BIM model. One possible approach is to program a tool that enables interoperability between the native software BIM (Revit Autodesk) and software that can implement Graph Theory (MatLAB), and then process it and gather data to drive the decision-making process (Figure 32).

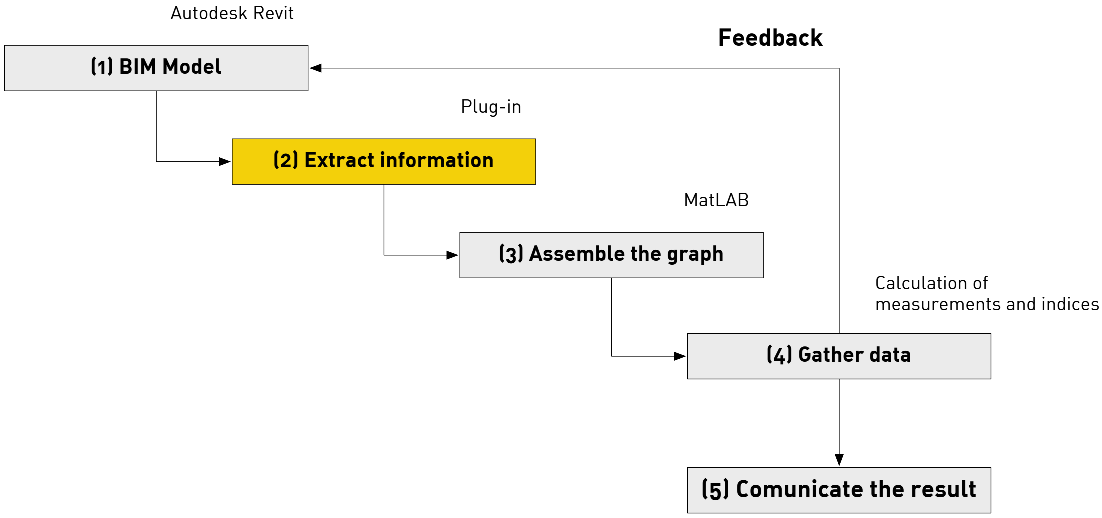


Figure 32 – Process of interoperability between BIM and Graph Theory

The current research used Autodesk Revit software as a BIM platform and MatLAB as a tool for displaying and calculating the measurements and the indices for the graph. The plug-in was written in C# using the software Visual Studio 2010, through which it was possible to create the class library.[187]

To create a plug-in it is necessary to use the Software Development Kit (SDK) for Revit, which can be downloaded from the Autodesk Revit Developer Center. A programming training session is available online with the “My first Revit plug-in” from Autodesk.

[187] The code is reported in Appendix D.

The plug-in is able to extract useful information for generating a space connectivity graph. To create this, we have to take into account four steps of recognition:

- Detection of the **building storeys**;
- Determination of **spaces**;
- Definition of **doors** and **windows** connected to those spaces;
- Definition of **stairs**, **ramps** and **elevators**.

During the programming phase **robustness against 3D modelling errors** was not considered; in any case the plug-in does not control possible errors such as not closing walls, separation of activities, overlapping of walls and so on. These gaps were obviously not intended by the modeller and should therefore be eliminated.

The output of the plug-in reads the information from a Revit Model and provides two lists of data (.csv file). One is the list of spaces (2 x n, described by ID and label) and the second the list of connections (5 x n, described by Source, Target, Type, ID, Label, Weight).

Table 4 – Spaces and connections list – First floor of the Mrs Thomas H. Gale House

List of Spaces		List of Connections			
Id	Label	Source	Target	Id	Weight
1	A1	1	2	1	1.0
2	1	2	3	2	1.0
3	2	2	4	3	1.0
4	n1	4	5	4	1.0
5	n5	5	6	5	1.0
6	5	5	8	7	1.0
7	6	5	9	8	1.0
8	4	6	7	6	1.0
9	n2	8	9	12	1.0
10	n3	9	4	9	1.0
11	3	9	10	10	1.0
12	n4	9	13	13	1.0
13	7	10	8	11	1.0
14	A2	10	12	14	1.0
		11	10	16	1.0
		12	11	15	1.0
		12	14	17	1.0

The relation of these two lists with specialist software (e.g. Gelphi or Mat LAB) generates the graph shown in Figure 33.

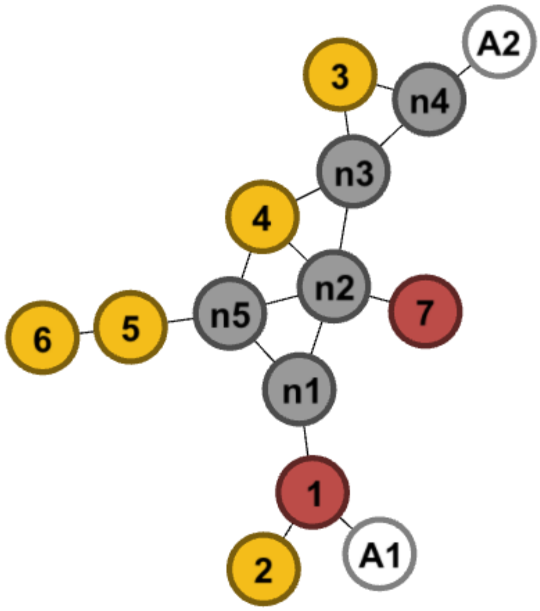


Figure 33 – Abstracted graph – First floor of the Mrs Thomas H. Gale House

Within MatLAB, it is then possible to run a routine to calculate the parameters, collect them and display them in any datasheet or graph representation.[188]

Some limitations need to be taken into account. The “space” must be indicated through the program (Revit) using the command “rooms” under the menu ”architecture”, and each room must be classified according to rigorous naming criteria.

The list of connections, however, is achieved through the recognition of the position of the “door” and then proceeds in reading, within the code of the Revit Model, the feature “from Room” and “to Room”. These characteristics allow us to extract the topological information and assemble the list of connection files.

Another limitation is related to the naming of spaces. The plug-in works through the recognition of a “tag” or “label” for each entity, except for generic space. For instance, stairs, elevators and ramps have to be indicated with NAME+NUMBER_OF_FLOOR-NUMBER_OF_PROGRESSIVE_ELEMENT (For instance, STAIR03-04, indicates the fourth stair on the third floor). For each space, it is necessary to indicate a name, otherwise the software will not recognize the entities.

[188] The code is reported in Appendix B.

A similar process can be conducted to develop a plug-in for IFC, especially since in the domain of 3D CAD modelling there is an abundance of different file formats. It is possible to program stand-alone software that can read any IFC file. The difference between the plug-in written for Revit and the stand-alone one for IFC lies in the classes for extracting topological information.

For instance, to extract information about the connection between two spaces, Revit uses the characteristics of “from Room” and “to Room”, which can be extracted and composed in a .csv file. For the IFC file this relationship between doors and spaces can exist via IfcRelSpaceBoundary. For many problems the approach to solving them is similar.

4.5.3 Validation of the plug-in

The validation of the plug-in is carried out by comparing (both visually and numerically) the results achieved from the automated procedure with the theoretical requirement (manually calculated), as well as comparing the graph achieved though Gelphi with the schematic graph achievable from direct observation of a layout distribution.

The plug-in for Revit allows the user to automatically generate a graph based on two .csv files using the software Gelphi, which creates a list of data for spaces and links. The plug-in was modified until the results met the theoretical requirements.

The following table shows a sample of the final tests performed that led to positive results.

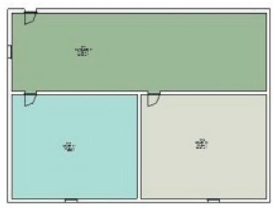
Test and elements	**Description**
V_01 – 1 level – generic doors	Test of recognition of just node end edges
V_02 – 1 level – generic doors and openings	Test of variation of type of junctions (doors, opening, proximity)
V_03 – 1 level – generic doors and openings	Test of relation with the outside
V_04 – 1 level – generic doors and openings	Test of division of the space
V_05 – 3 levels – stair	Addition of the stair (vertical core)
V_06 – 3 levels – stair and elevator	Addition of the elevator (vertical core)

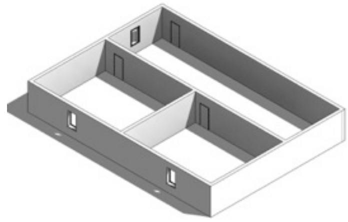
Evidence V_01

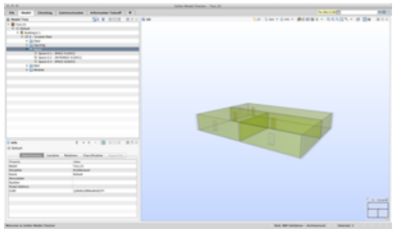
Description:

The spaces are connected with generic doors.

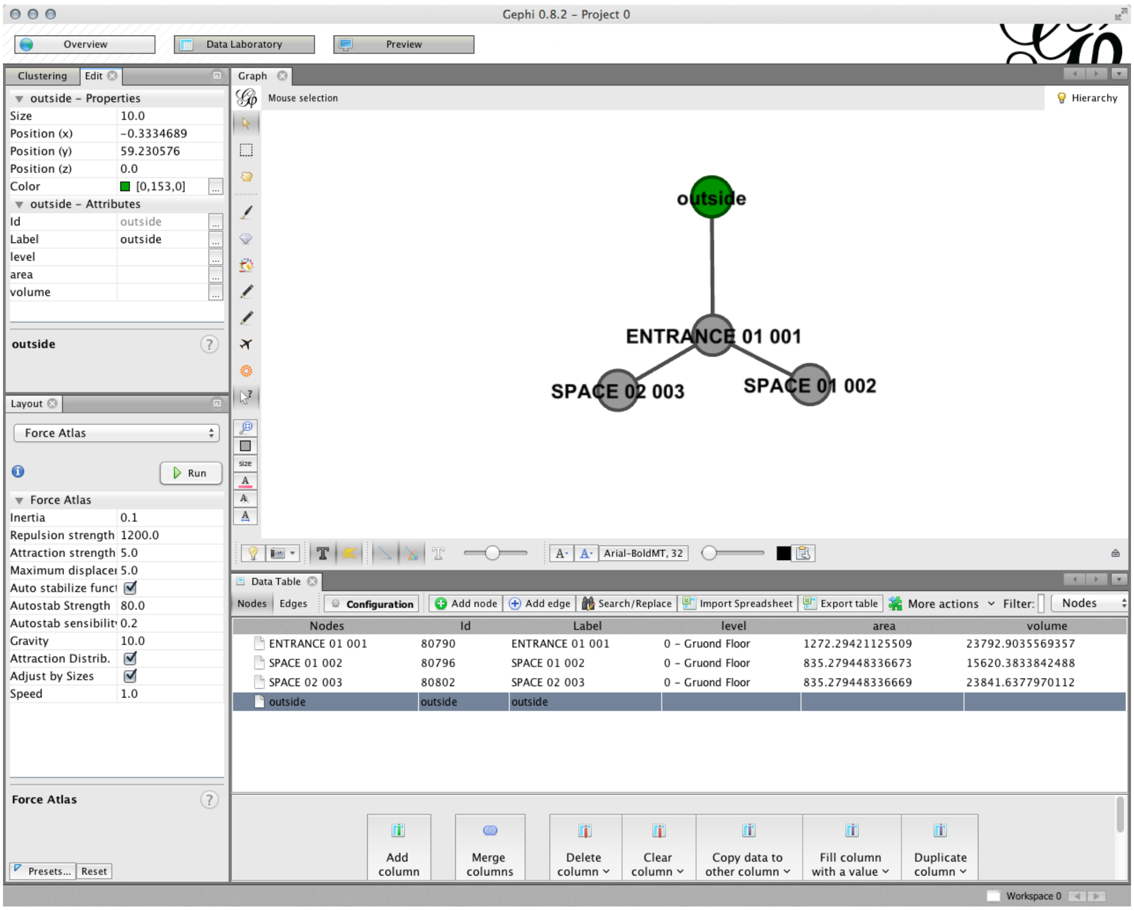
Entrance has a direct connection with the outside.







Reference plan (Autodesk Revit) | 3d Model (Autodesk Revit) | IFC representation (SMC)



Automatically generated graph for V_01 (Gelphi)

Note:

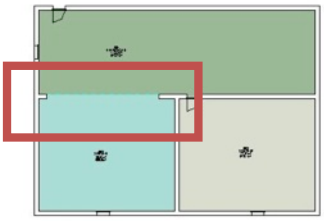
Result: Verified

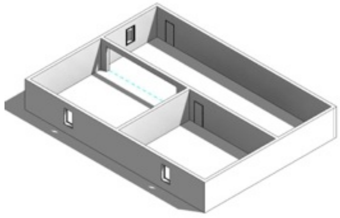
Evidence V_02

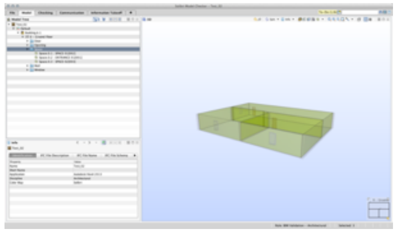
Description:

The spaces are connected with a generic door and with an opening.

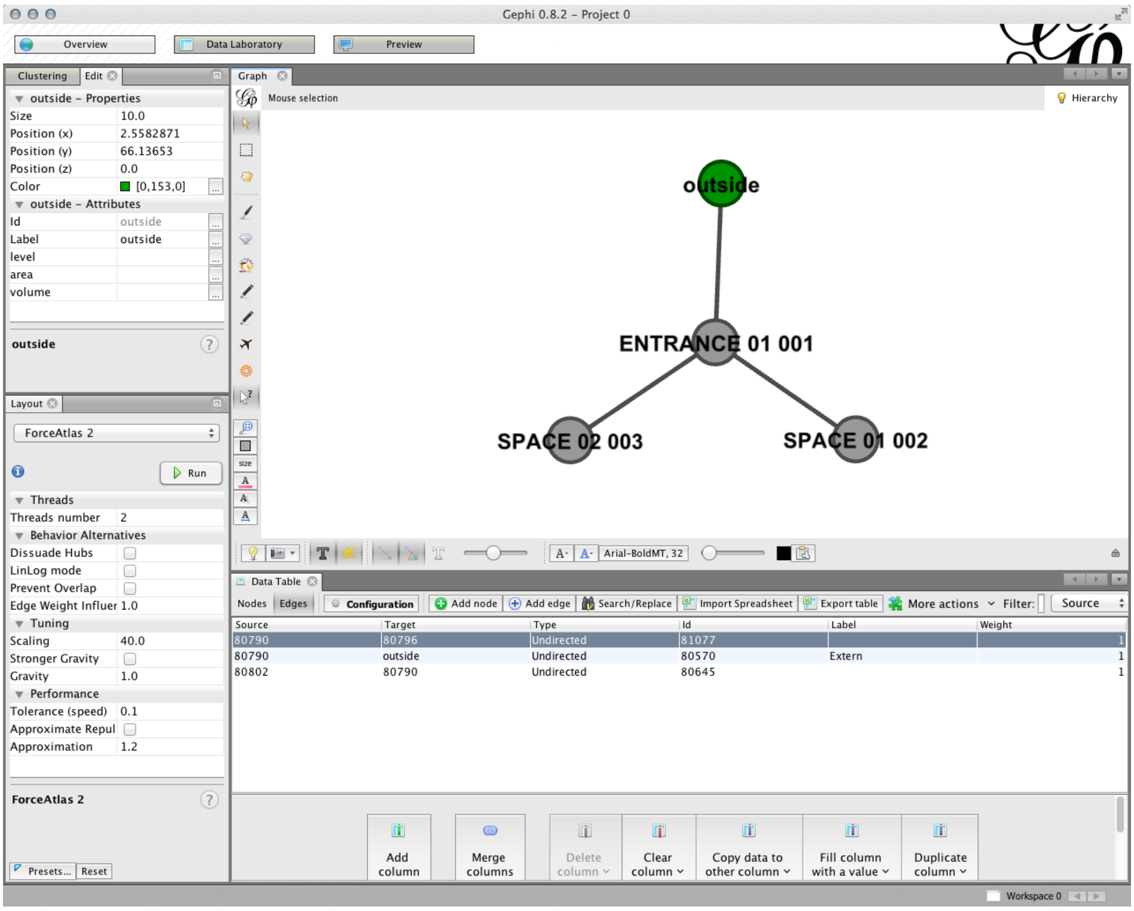
Entrance has a direct connection with the outside.







Reference plan (Revit) | BIM Model (Revit) | IFC representation (SMC)



Automatically generated graph for V_02 (Gelphi)

Note:

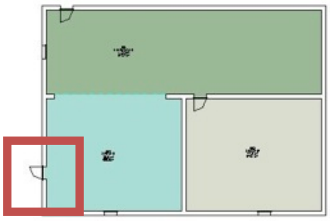
Result: Verified

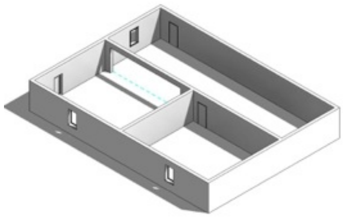
Evidence V_03

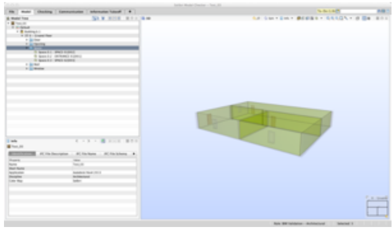
Description:

The spaces are connected with a generic door and with an opening.

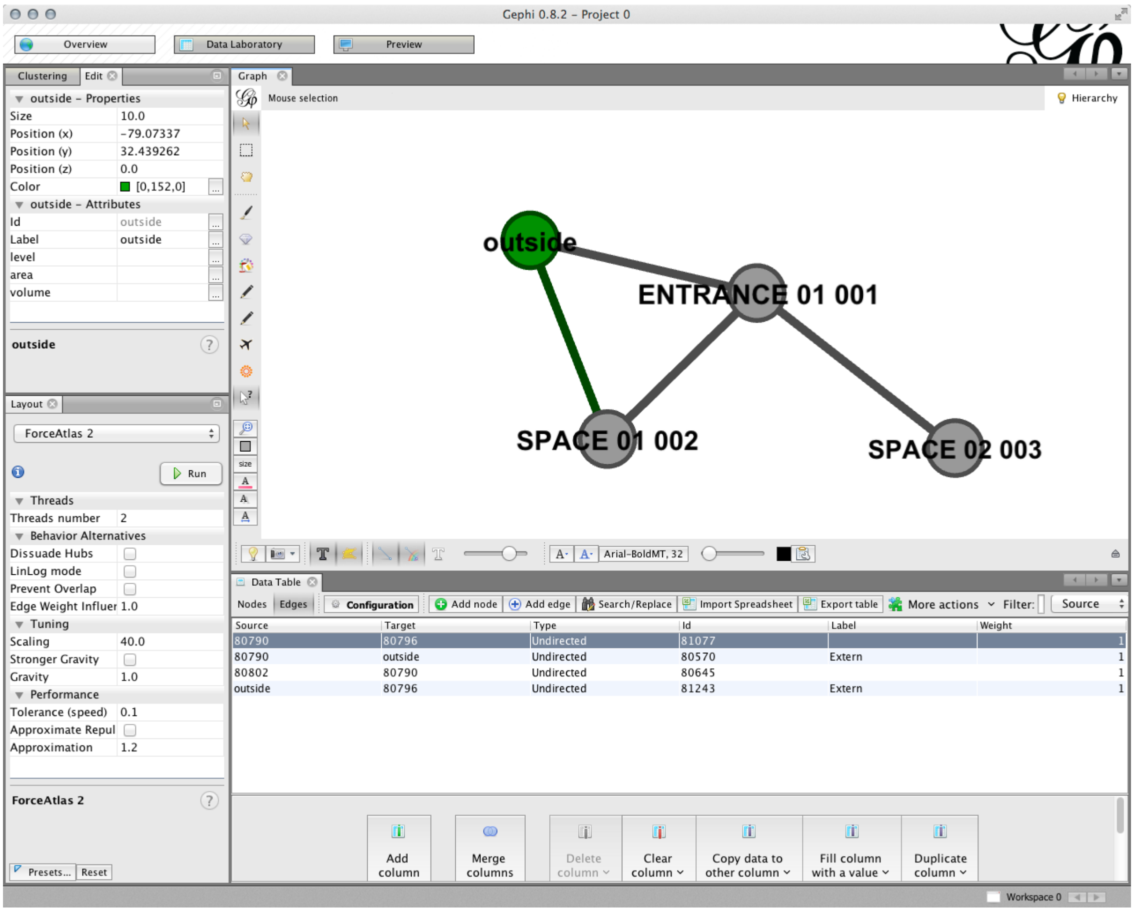
Entrance and Space 01 have a direct connection with the outside.







Reference plan (Autodesk Revit) | BIM Model (Autodesk Revit) | IFC representation (SMC)



Automatically generated graph for V_03 (Gelphi)

Note:

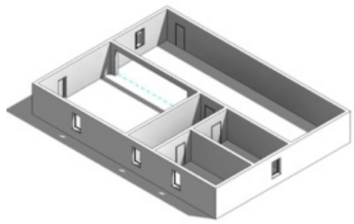
Result: Verified

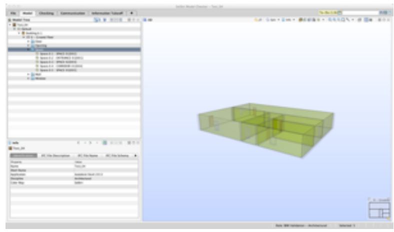
Evidence V_04

Description:

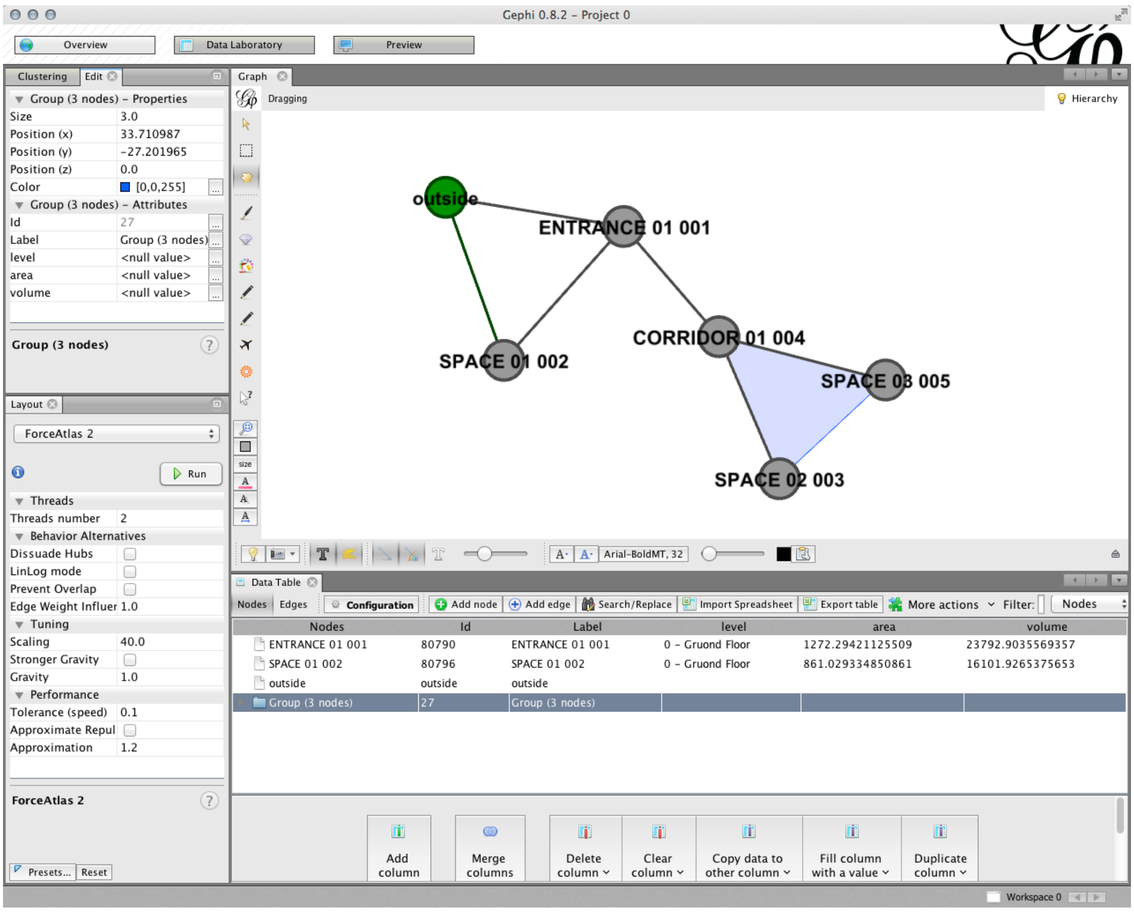
In reference to V_03, one of the spaces is divided into a corridor and two more spaces.

Entrance and Space 01 have a direct connection with the outside.





Reference plan (Autodesk Revit) | BIM Model (Autodesk Revit) | IFC representation (SMC)



Automatically generated graph for V_04 (Gelphi)

Note:

The light blue colour in the graph indicates the new group of spaces that has been added.

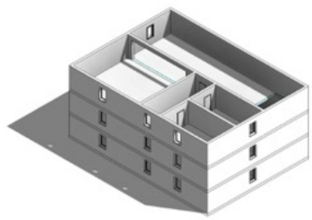
Result: Verified

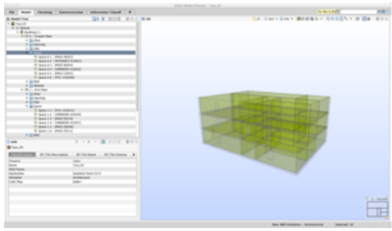
Evidence V_05

Description:

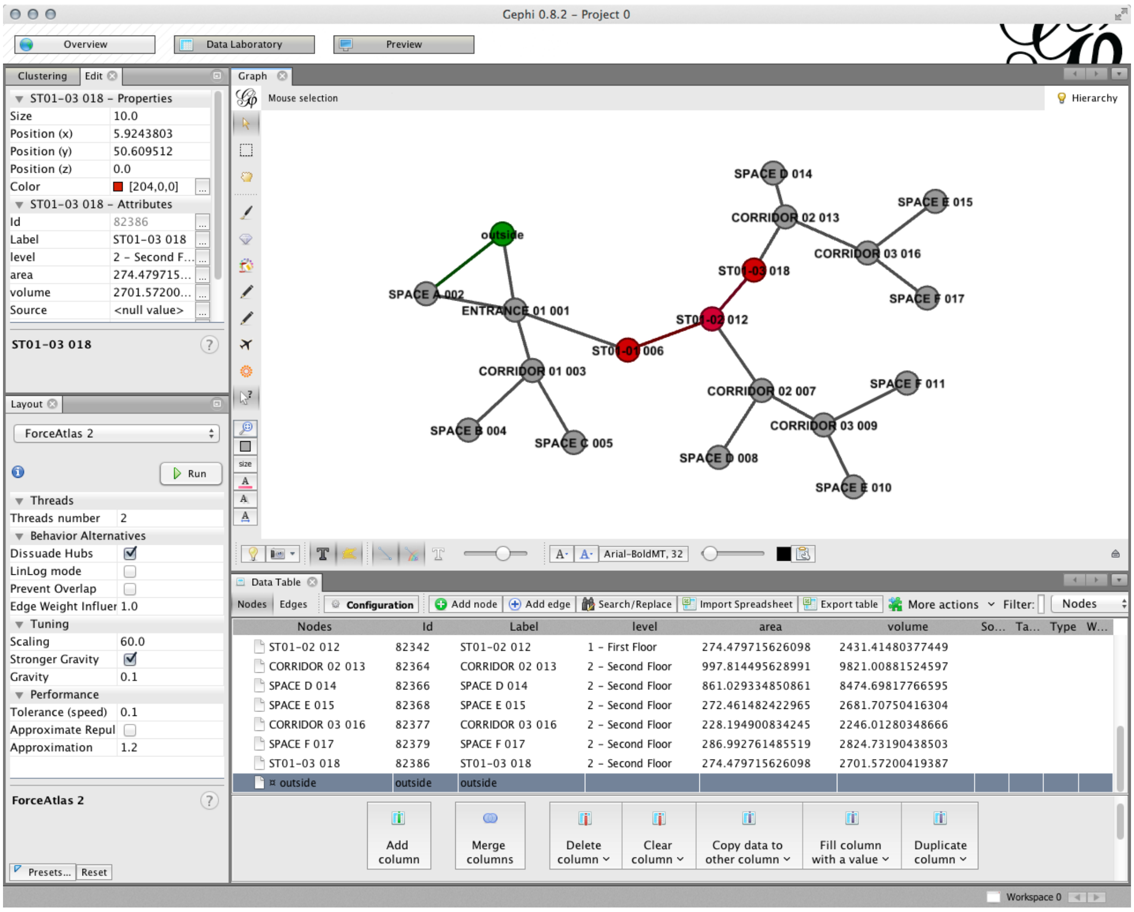
In reference to V_04, the stair is inserted next to the corridor and the floor is copied twice.

Entrance and Space 01 have a direct connection with the outside.





Reference plan (Autodesk Revit) | BIM Model (Autodesk Revit) | IFC representation (SMC)



Automatically generated graph for V_04 (Gelphi)

Note:

The colour red in the graph represents the vertical path of the stair.

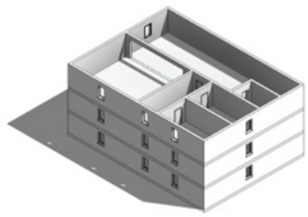
Result: Verified

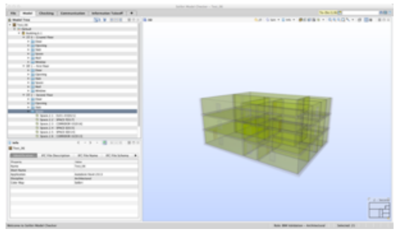
Evidence V_06

Description:

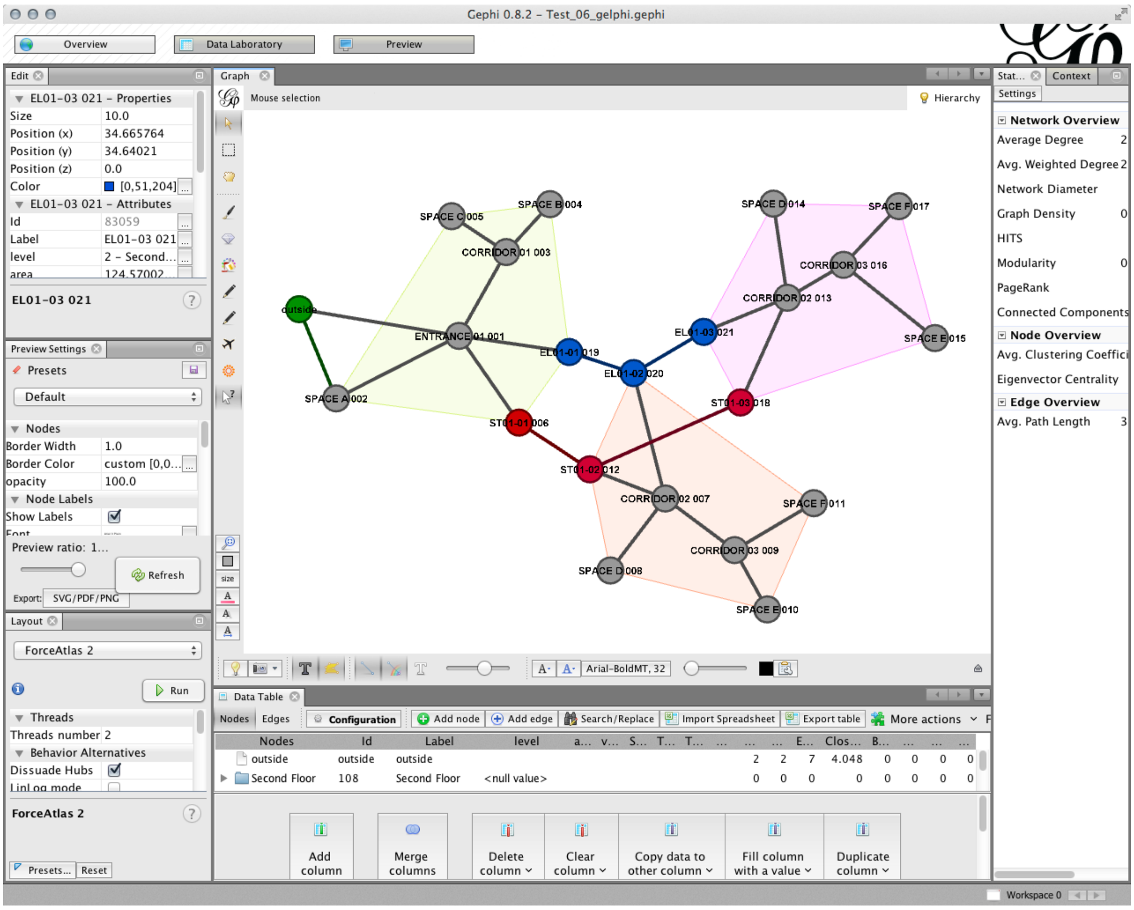
In reference to V_05, an elevator has been added, next to the corridor and the stair.

Entrance and Space 01 have a direct connection with the outside.





Reference plan (Autodesk Revit) | BIM Model (Autodesk Revit) | IFC representation (SMC)



Automatically generated graph for V_04 (Gelphi)

Note:

Each storey is highlighted in one colour and gathered into a group.

It is easy to verify that the vertical paths (both stair and elevator – red and blue) are correct.

Result: Verified

4.6 Parameter behaviour

The aim of this experiment is to understand the presence of a correlation between a specific design action that imposes a re-design of a layout distribution, and parameters gathered from Graph Theory.[189] This first set of experiments was performed as a “finding investigation” to focus on showing the relationship between parameters gathered from Graph Theory and a particular pattern of a specific layout distribution. The analysis was carried out by examining abstract patterns (rather than any specific type of building) in order to gather information about the behaviour of space aggregations (generalization of the method).[190] Although the aggregation of spaces can be varied and diversified, we are particularly interested in those recurrent patterns which we find throughout the history of architecture, based on criteria of seriality and polarity of space aggregation.[191]

The analyses were carried out by starting from an initial condition and measuring the behaviour of the parameters when there was a “modification” to the layout distribution. For instance, starting from a specific layout configuration the layout was changed by demolishing internal partitions or fragmenting the spaces. Another modification that was used in multiple floor buildings was to add a vertical core in different zones of the building. Alterations to parameters as a function of these modifications of layout distribution were tracked and reported in the text. Several BIM models were developed using Revit Autodesk, and then the data were imported into Gelphi, Excel and MatLAB in order to calculate the parameters.

The cases analysed are shown in the picture below, suing a BIM software (in this case Autodesk Revit). With custom software, it is possible to extract information useful for post-processing with Gelphi and MatLAB. The patterns taken into account are simplified schemes of recurrent space aggregations in architecture. These reference patterns have been set out in Figure 34.

[189] See Appendix B.

[190] Some of these patterns can easily be associated with a particular building type, such as office buildings, hospitals, libraries or airports, but in this context the type of building is irrelevant. This factor only becomes important when we start to consider in detail the relationship between spaces and the design specifications.

[191] See section 2.2.3 – Interventions on specialized buildings.

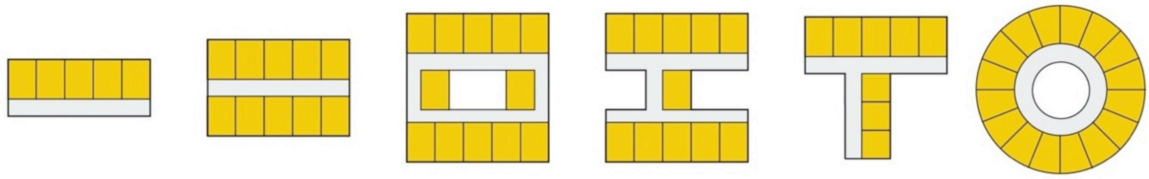


Figure 34 – Test 01 – spaces pattern[192]

Starting from an initial configuration, spaces were added to the original pattern in order to create a population of significant cases to analyse. Subsequently, an internal modification of the layout was applied, such as the removal of an internal wall, the addition of an access point for the building or, in the case of multiple floors, modification of the position of the vertical core. We might expect to obtain a better value in terms of connectivity when an open space or a configuration that assumes a partially open space is created and, in the case of adding a vertical core, we would expect to find a better value if the core were positioned in a barycentric position. It is also important to evaluate the results critically from a mathematical point of view and to always compare them with the architectural criteria, because it is not obvious that the two requirements have to be coincident and lead to the same conclusion (positive or negative evaluation). For instance, if we look at some modern architecture we frequently find examples of this, especially in certain locations of outstanding natural beauty where high value is attached to the view of the landscape. In such cases we might wish to enhance the analysis by including an evaluation of possible perceptions from the site, rather than a pure circulation optimization. On the other hand, for building types such as hospitals and airports the functional aspect often comes to the fore. In any case, the architect can decide to prioritize aesthetic aspects as well as circulation factors.

The BIM models were generated through Autodesk Revit using a particular dimensional convention: one space unit is 5 x 5 x 3 meters and the corridor is 3 meters wide and as long as is needed to reach every space. Regarding the number of spaces, these have been used in multiples of 10, 16, 20, 30 and 60 spaces. Moreover, we compared only similar patterns that had the same number of spaces. For realizing the pattern we used the following configuration: 5, 10, 16, 20, 30 and 60 spaces. Other considerations can be summarized in the following list:

[192] Generic rooms are indicated in yellow and the corridor path is in grey.

1) The number of “nodes” (n) used is not coincident with the number of “rooms” because we must also consider the “outside node” and all the “circulation nodes”;

2) The space “corridor” is decomposed into a series of spaces made up of the sum of the various “circulation nodes”;

3) The area and the volume were extracted directly from Autodesk Revit;

4) The number of people within the building was obtained by counting two units for each “functional space”, not considering the space for corridors and connections.

The correctness of all the case studies was guaranteed by means of a direct comparison with the output given from Gelphi. The graph produced by the latter method was compared with a graph drawn by hand. Some results of the analyses conducted are shown in the following pages.

TP_01 – Singular linear

TP_01 is the first case analysis and it consists of a simplification of a linear building. It shows a row of spaces aggregated in a single level with a single access indicated by the back arrow. Figure 35 shows the cases analysed.

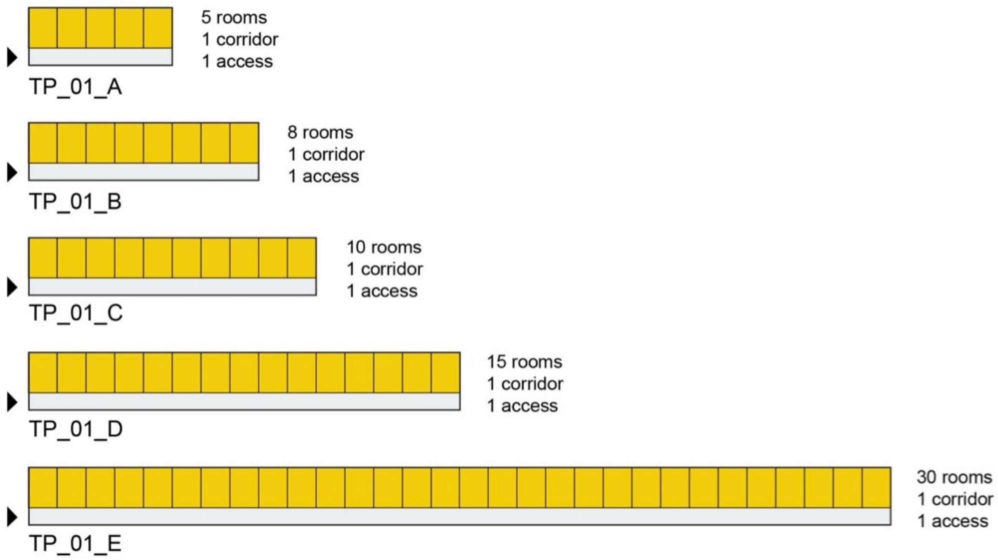


Figure 35 – TP_01

After deciding on the module aggregation, it was possible to draw the support structure by hand. This process is important because it is one of the methods for validating the result achieved through MatLAB and Gelphi.

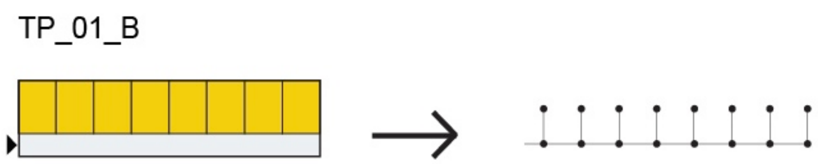


Figure 36 – TP_01_B support structure

The process began with the BIM model gathered from Revit. This was a simplified model that included only walls, floors, doors, windows and the information about rooms (Figure 37).

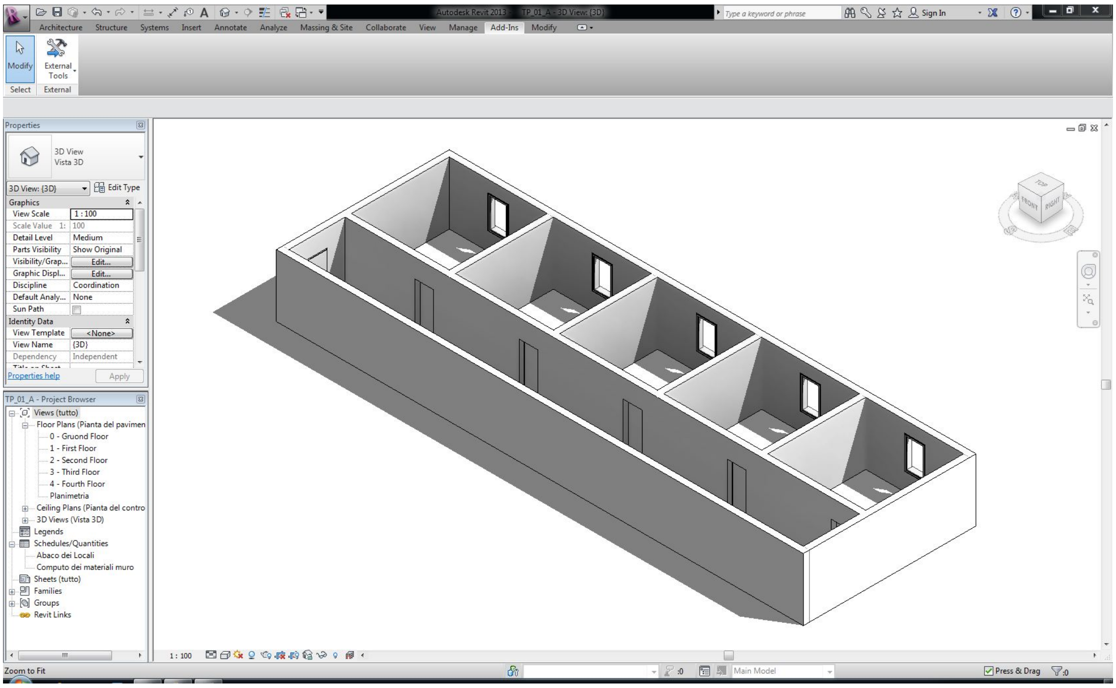


Figure 37 – TP_01 Revit Model

The table below (Table 5) shows the numerical results obtained from the analysis conducted with Gelphi and MatLAB.

Table 5 – Numerical results for TP_01

	v (space)	e (edges)	A (surface)	V (volume)	L(g) (total leght)	PE (people)	p (sub-cycle)	u (cycle)	d (diameter)	gd (density)	lg (av. leght)	η	Θ	β	α	γ	C_{tot} (total cost)	MST (cost)
TP_01_A	16	15	177	532	25	10	1	0	11	0,125	4,41	1,67	0,63	0,94	0,00	0,36	18,0	18,0
TP_01_B	25	24	284	852	40	16	1	0	17	0,080	6,43	1,67	0,64	0,96	0,00	0,35	28,5	28,5
TP_01_C	31	30	355	1065	50	20	1	0	21	0,065	7,76	1,67	0,65	0,97	0,00	0,34	35,5	35,5
TP_01_D	46	45	533	1599	75	30	1	0	31	0,043	11,10	1,67	0,65	0,98	0,00	0,34	53,0	53,0
TP_01_E	91	90	1066	3200	150	60	1	0	61	0,022	21,11	1,67	0,66	0,99	0,00	0,34	10,5,5	10,5,5

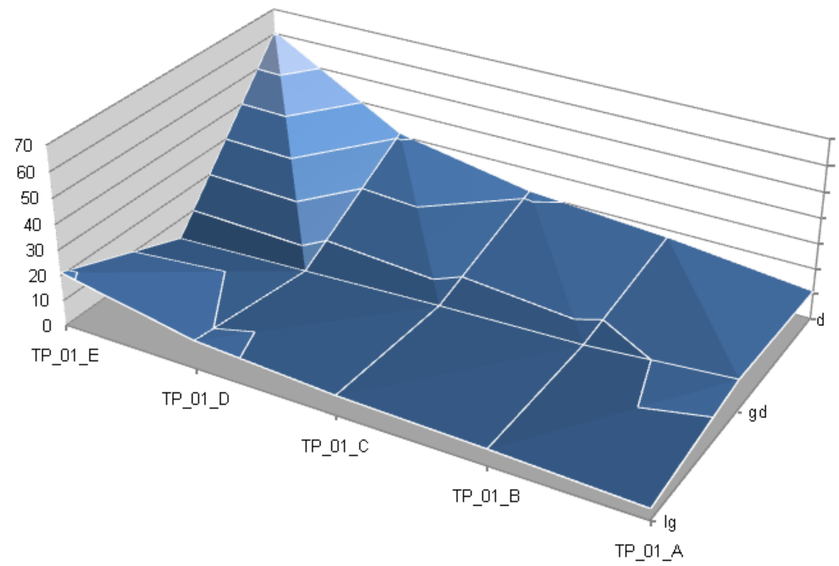


Chart 1 – Trends for the parameters d and lg regarding TP_01

From studying the data it is possible to state that there are trends in certain parameters as a function of the increasing number of spaces. We can affirm that:

- the diameter (d) and the average path (lg) increase in relation to the number of spaces while, on the contrary, the density (gd), that represents the distance of the analysed graph from a complete graph, decreases gradually.
- η and α, two of the dimensionless parameters, are constant, because η is a function of the ratio between L(g) – the total length and e – the number of edges, and α is a function of u – the number of cycles which in any linear typology, except for more complex architectural solutions, is always zero. For η, in this particular case, the ratio is constant because the analysis does not take into account any internal fragmentation. This parameter is helpful only in cases where there is an internal modification but, at the moment, for this value we cannot obtain any information.
- Θ and β grow according to the increase in the number of spaces, while ϒ decreases.

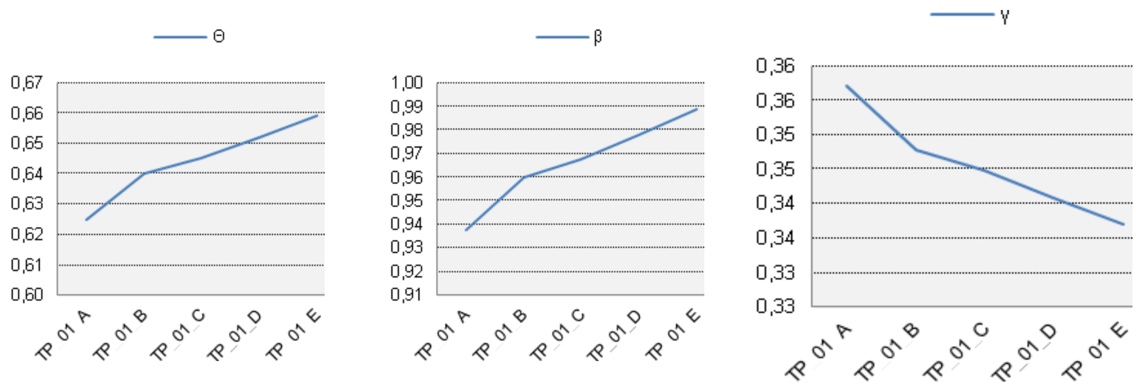


Chart 2 – Trends for the dimensionless parameters Θ, β and ϒ regarding TP_01

Taking the set under analysis, we applied internal modifications to the layout in two ways: firstly by removing the internal partitions and, secondly, considering only the TP_01_C case, by adding several entrances, as shown in Figure 38.

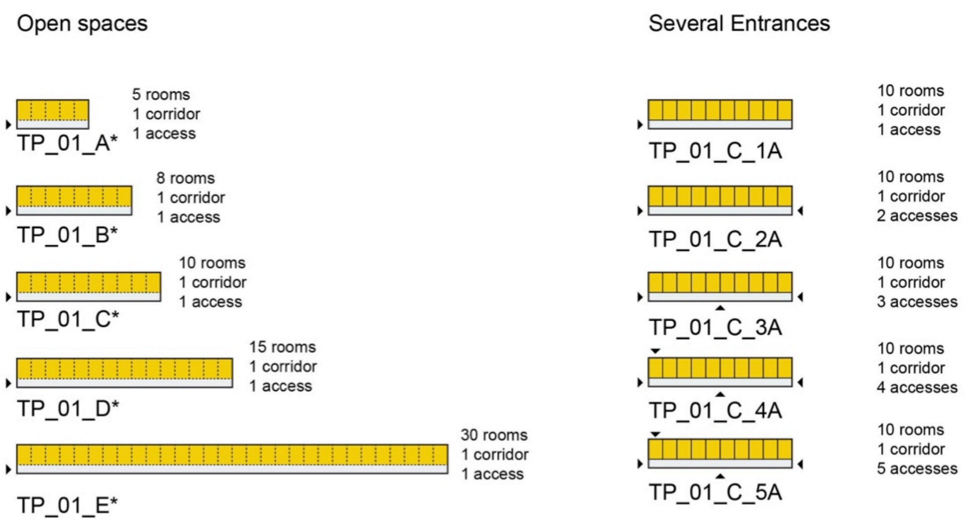


Figure 38 – TP_01 modification of the layout

Before showing the result it is necessary to outline some considerations: the removal of walls has the consequence of generating a single environment. If we consider this, without any sort of separation, we might be tempted to consider that the number of nodes will be 1 and the value of edges will be zero. Under these conditions there would seem to be no sense in proceeding with the analysis because the parameters calculated would not be comparable with those previously shown. On the contrary, however, it does make sense to substitute the walls with virtual partitions for dividing specific functions. The parameters, in this case, are highly influenced by the design decision.

The following table shows the result for the two modification actions: Table 6 refers to the demolition of internal partitions and Table 7 to the addition of several entrances.

Table 6 – Numerical result for TP_01* with demolition of internal partitions

	v (space)	e (edges)	A (surface)	V (volume)	L(g) (total leght)	PE (people)	p (sub-cycle)	u (cycle)	d (diameter)	gd (density)	lg (av. leght)	η	Θ	β	A	γ	C_{tot} (total cost)	MST (cost)
TP_01_A*	16	20	177	532	25	10	1	5	10	0,167	4,08	1,25	0,63	1,25	0,19	0,48	37,5	23,5
TP_01_B*	25	32	284	852	40	16	1	8	16	0,107	6,09	1,25	0,64	1,28	0,18	0,46	61,5	38,5
TP_01_C*	31	40	355	1065	50	20	1	10	20	0,086	7,43	1,25	0,65	1,29	0,18	0,46	77,5	48,5
TP_01_D*	46	60	533	1599	75	30	1	15	30	0,058	10,77	1,25	0,65	1,30	0,17	0,45	117,5	73,5
TP_01_E*	91	120	1066	3200	150	60	1	30	60	0,029	20,77	1,25	0,66	1,32	0,17	0,45	237,5	148,5

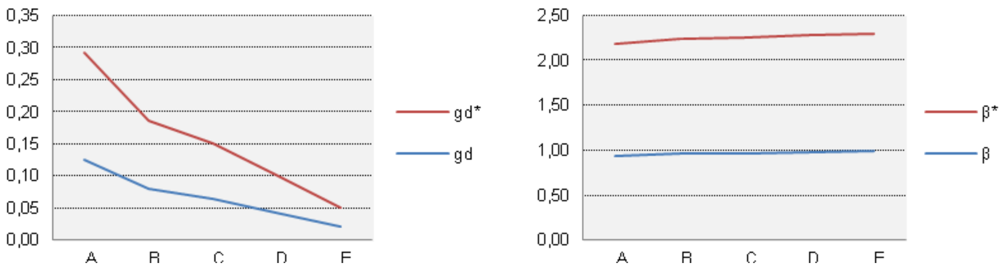


Chart 3 – Comparison between TP_01 and TP_01* for the values gd and β

Observing the result achieved, the total demolition of internal partitions led to an increase of the connectivity expressed by the values gd and lg but also expressed by dimensionless parameters, in particular β.

α, compared to TP_01, is not negative and has a value due to the presence of cycles in the internal distribution. That means it is possible to reach a space by following several types of path. Moreover, as expected, there is an increase in the density and a reduction of the average length - l(g) compared to the previous version with walls.

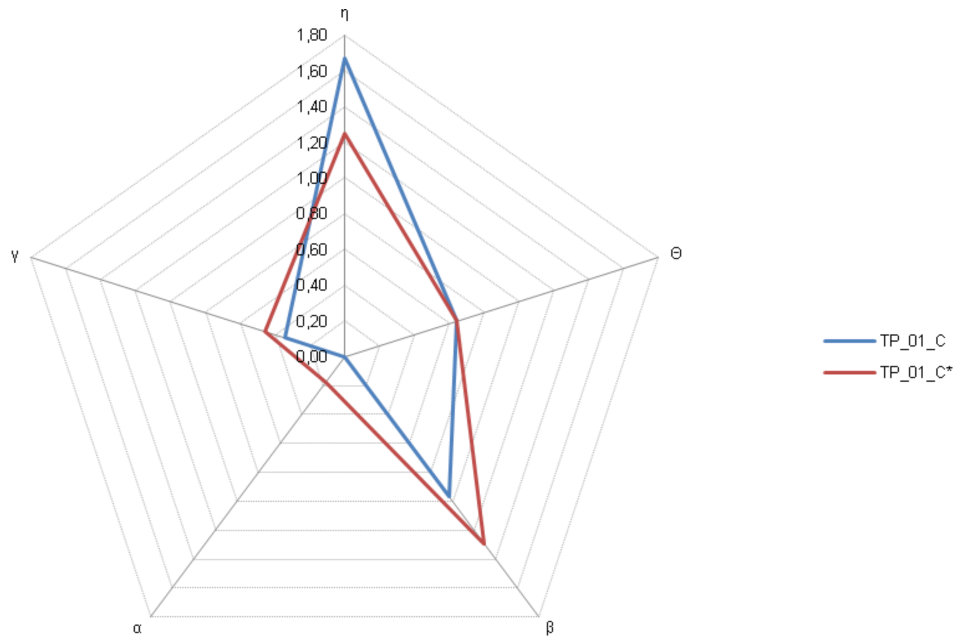


Chart 4 – Behaviour in case of realization of an open space

With regard to the dimensionless parameter, Chart 4 shows the comparison between two solutions to a row of consecutive spaces (TP_01_C and TP_01_C*).

The parameters have confirmed the expected result: there is a generic improvement in TP_01_C about connectivity (α, β, η and γ).

Another test was carried out on modifying the number of entrances, as shown on the right of Figure 38.

Table 7 – Numerical result for TP_01_C additions of several entrances

	v (space)	e (edges)	A (surface)	V (volume)	L(g) (total leght)	PE (people)	p (sub-cycle)	u (cycle)	d (diameter)	gd (density)	lg (av. leght)	η	Θ	β	α	γ	C_{tot} (total cost)	MST (cost)
TP_01_C1A	31	30	355	1065	50	20	1	0	21	0,065	7,76	1,67	0,65	0,97	0,00	0,34	35,5	35,5
TP_01_C2A	31	31	355	1065	50	20	1	1	12	0,067	6,05	1,61	0,65	1,00	0,02	0,36	37,0	35,5
TP_01_C3A	31	32	355	1065	50	20	1	2	12	0,069	5,10	1,56	0,65	1,03	0,04	0,37	38,5	35,5
TP_01_C4A	31	33	533	1599	50	20	1	3	12	0,071	5,00	1,52	0,65	1,06	0,05	0,38	40,0	35,5
TP_01_C5A	31	34	1066	3200	50	20	1	4	12	0,073	4,96	1,47	0,65	1,10	0,07	0,39	41,5	35,5

Observing Table 7, some considerable changes can be noted.

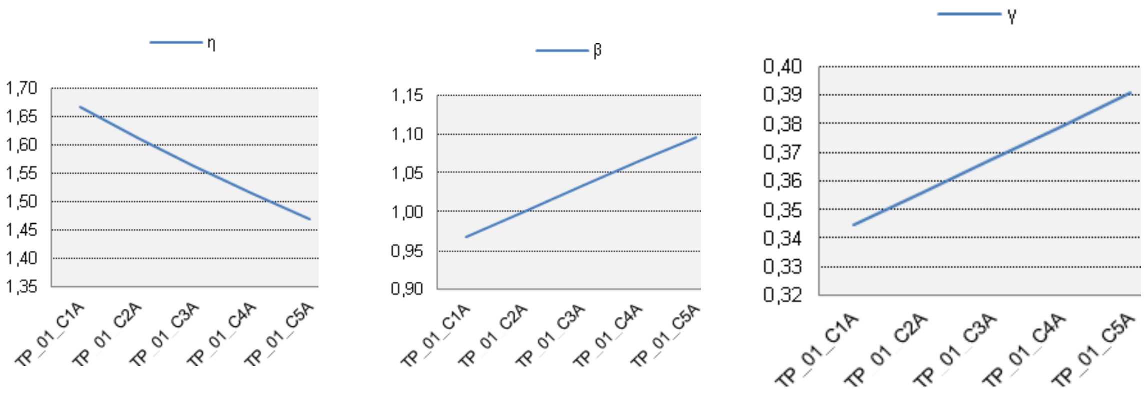


Chart 5 - Trends for the dimensionless parameters η, β and ϒ for only TP_01_C

As shown in Chart 5, only η decreases linearly while β and ϒ decrease in accordance with what was expected, because adding entrances in the building means augmenting the connectivity. Regarding η, in accordance with the definition given in Appendix B, there is a clear indicator of the fragmentation of spaces.

In addition, a variation of the diameter is detectable when the second entrance is added. The value moves from 21 to 12 because a central room can be reached from the exterior with half of the movement within the network, rather than crossing all the nodes present in the configuration when there was only one entrance.

TP_02 – Double linear

In TP_02 the analysis continues, doubling the number of spaces on the other side of the corridor. The space continues to be aligned in one direction and the building has only one floor. The access still remains in the position indicated by the black arrow. In the figure below (Figure 39) we can see the cases analysed.

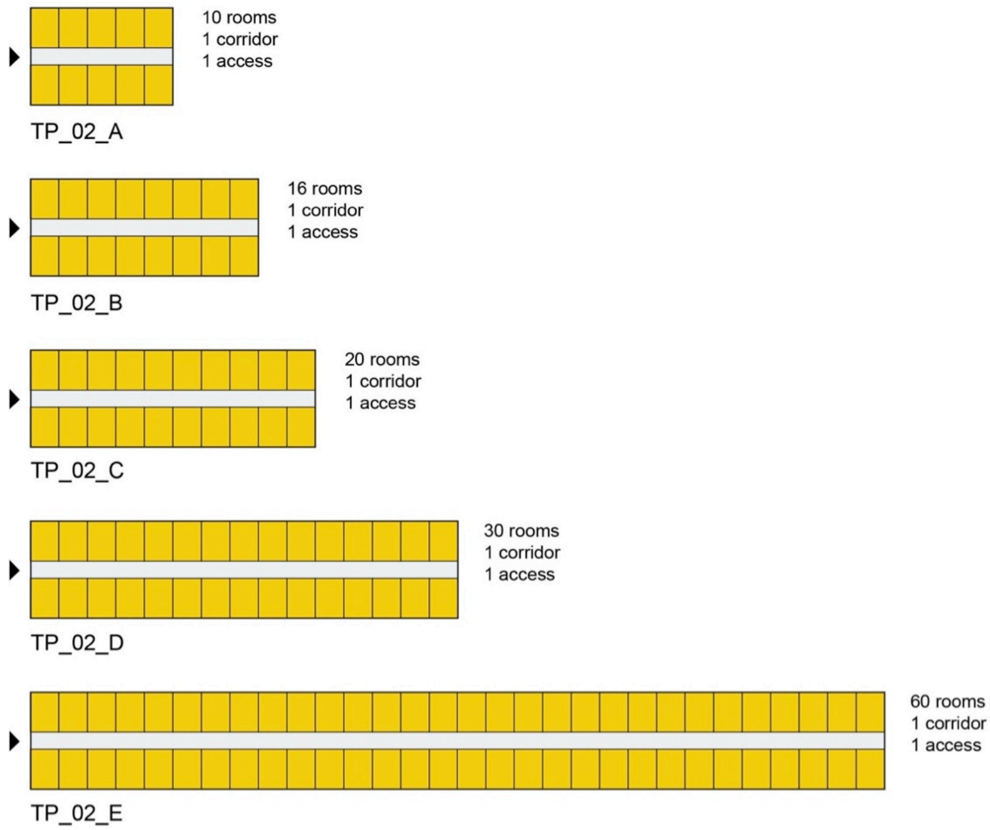


Figure 39 – TP_02

The figure below shows the support structure for the case TP_02_B.

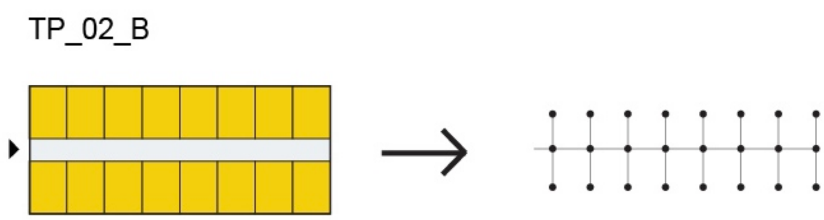


Figure 40 – TP_02_B support structure

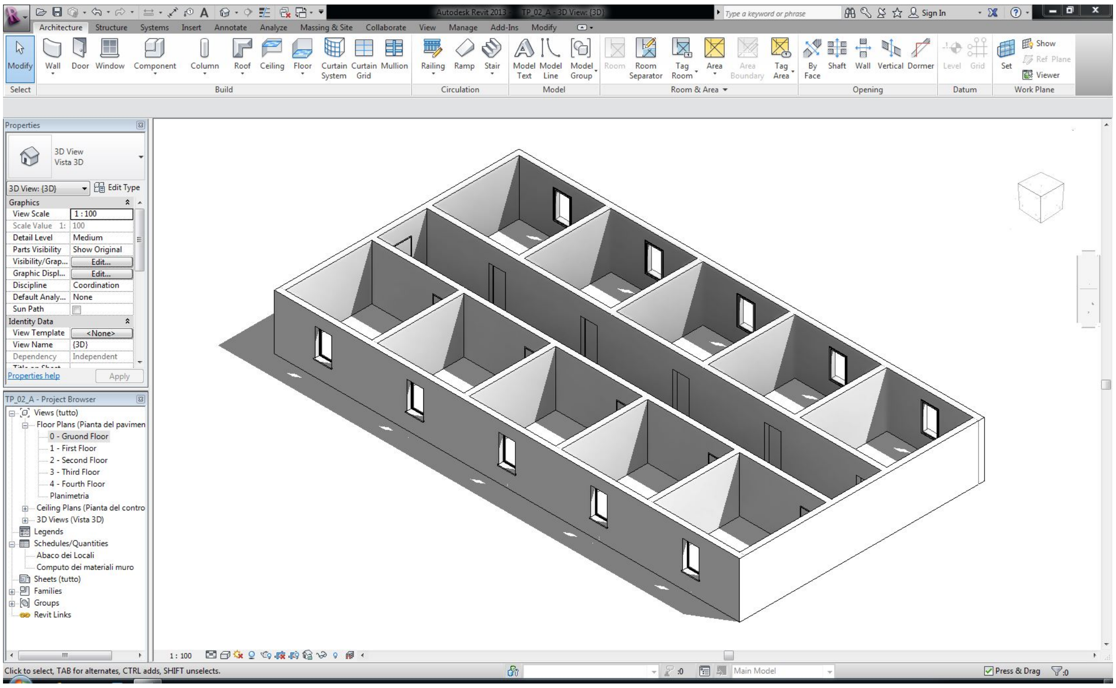


Figure 41 – TP_02_B Revit Model

The table below (Table 8) shows the numerical results obtained from the analysis.

Table 8 – Numerical result for TP_02

	v (space)	e (edges)	A (surface)	V (volume)	L(g) (total leght)	PE (people)	p (sub-cycle)	u (cycle)	d (diameter)	gd (density)	lg (av. leght)	η	Θ	β	α	γ	C_{tot} (total cost)	MST (cost)
TP_01_A	21	20	287	862	50	20	1	0	11	0,09	4,62	2,50	0,95	0,95	0,00	0,35	25,5	25,5
TP_01_B	33	32	460	1381	80	32	1	0	17	0,06	6,64	2,50	0,97	0,97	0,00	0,34	40,5	40,5
TP_01_C	41	40	576	1728	100	40	1	0	21	0,04	7,98	2,50	0,98	0,98	0,00	0,34	50,5	50,5
TP_01_D	61	60	864	2593	150	60	1	0	31	0,03	11,3	2,50	0,98	0,98	0,00	0,34	75,5	75,5
TP_01_E	121	120	1729	5188	300	120	1	0	61	0,01	21,3	2,50	0,99	0,99	0,00	0,34	150	150

Through this case the same behaviour as TP_01 is, in general, confirmed, with the only difference being that the parameters are slightly amplified or decreased due to the doubling of the spaces.

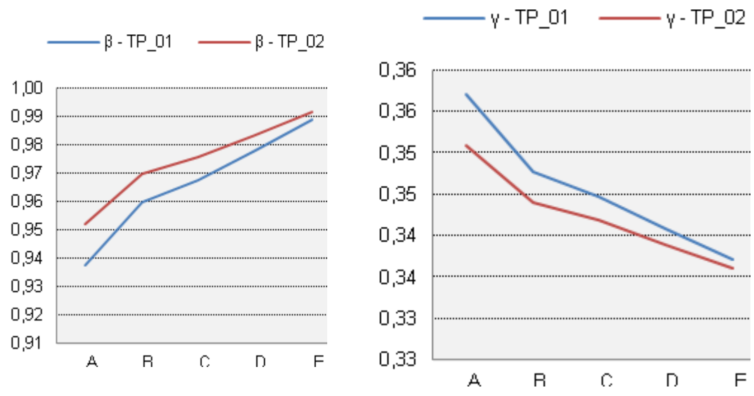


Chart 6 – Comparison between TP_01 and TP_02 for the values of β and ϒ

In fact, the higher value of β indicates a higher complexity of the graph. As we augment the number of spaces, it is natural that ϒ also falls. This value indicates the level of connectivity but in a progression in time: this result makes more sense if used for the evaluation of a design solution that undergoes a series of changes rather than evaluating only static cases.

Θ indicates the traffic within the building. This value is calculated by evaluating the maximum number of people that could be received by the building. This value has to be used in case of modification and comparison between several design solutions. In this case of static consideration it does not give significant information because the number of people was considered as proportional to the number of spaces.

Comparing the diameter (d) of TP_02 and TP_01, the values are constant for both cases. This is due to the fact that if we want to calculate the maximum distance between two spaces, it makes no difference if it is placed on the left or on the right in respect to the corridor.

Also in this case α remains null because there is no cycle inside the case analysed.

TP_03 – Court type

TP_03 gives different information due to its court-type shape that evolves and increases in the horizontal direction. In addition the hypothetical parameter has been calculated hypothesizing a fragmentation of the internal space of a particular condition. The access remains constant in all cases, indicated by the arrow. The figure below (Figure 42) shows the cases analysed.

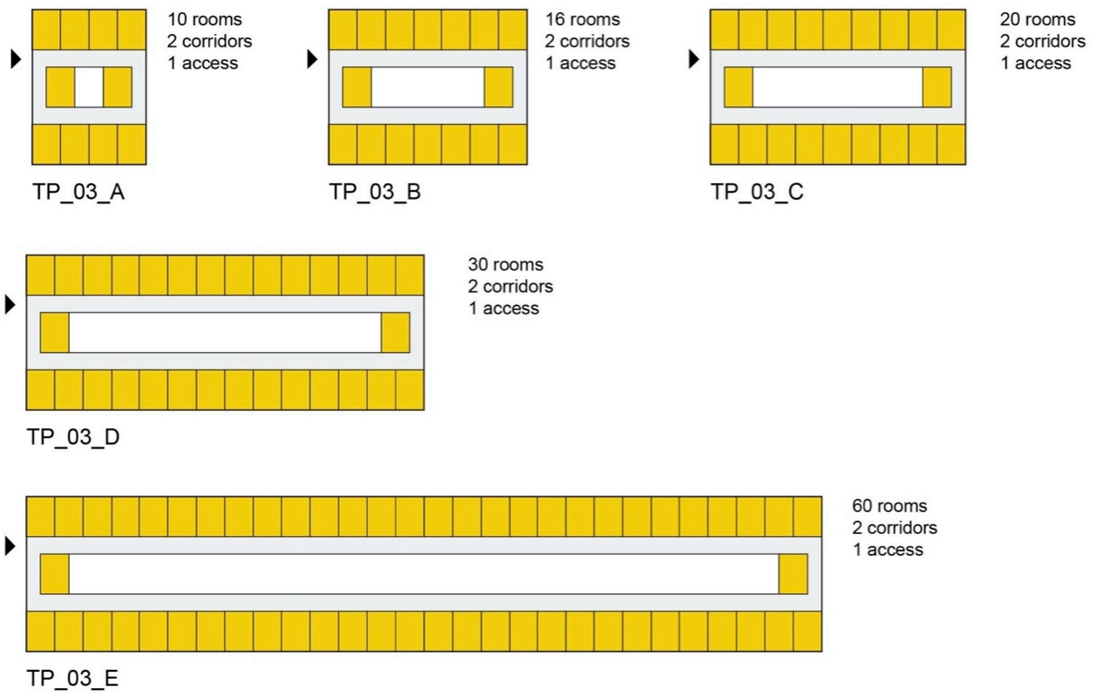


Figure 42 – TP_03

The figure below shows the support structure for the case TP_03_B.

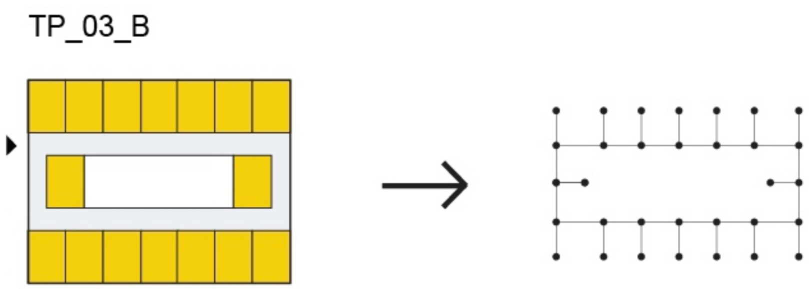


Figure 43 – TP_03_B support structure

The table below (Table 9) shows the numerical results from the analysis.

Table 9 – Numerical result for TP_03

	v (space)	e (edges)	A (surface)	V (volume)	L(g) (total leght)	PE (people)	p (sub-cycle)	u (cycle)	d (diameter)	g_d (density)	l_g (av. leght)	η	Θ	β	α	γ	C_{tot} (total cost)	MST (cost)
TP_03_A	31	32	358	1076	50	20	1	2	12	0,069	5,66	1,56	0,65	1,03	0,04	0,37	38,5	35,5
TP_03_B	49	50	643,4	1930	80	32	1	2	18	0,043	8,63	1,60	0,65	1,02	0,02	0,35	59,5	56,5
TP_03_C	61	62	714,6	2143,9	100	40	1	2	22	0,034	10,62	1,61	0,66	1,02	0,02	0,35	73,5	70,5
TP_03_D	91	92	1070	3211	150	60	1	2	32	0,022	15,61	1,63	0,66	1,01	0,01	0,34	108,5	105,5
TP_03_E	175	176	2067	6201	300	120	1	2	60	0,012	29,60	1,70	0,69	1,01	0,01	0,34	206,5	203,5

Observing the data achieved, it is possible to detect a general increase of the parameters that indicate connectivity, such as β, α and also ϒ. The trends are shown in Chart 7.

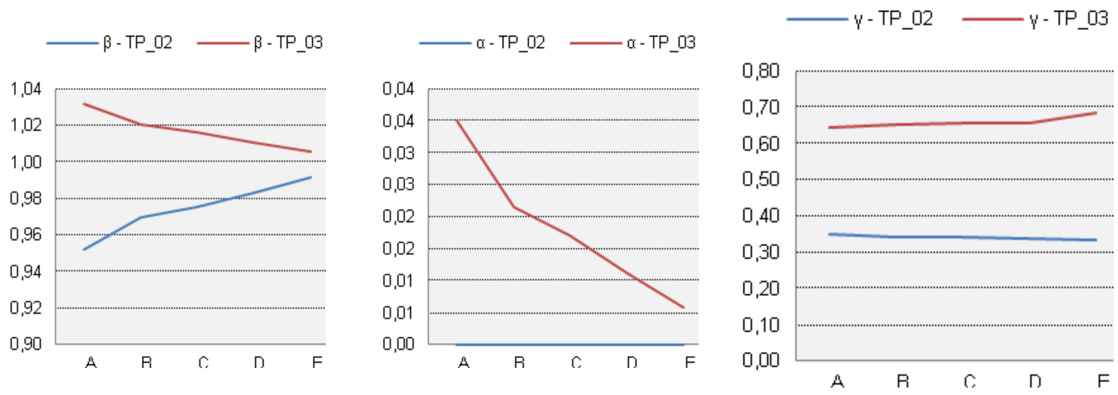


Chart 7 – Comparison between TP_02 and TP_03 for the values of β, α and ϒ

More information from comparing all the data can be found below, in the case study section.

An additional experiment considering a different path of aggregation was also performed, as shown in Figure 44. This was to validate the fact that we had assumed only one aggregative direction of expansion of the form.

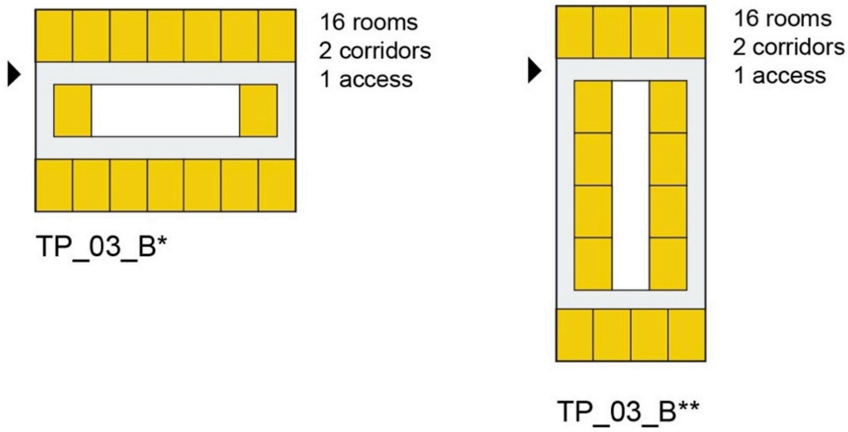


Figure 44 – TP_03 and different direction of aggregations

As shown in Table 10 the two distributions present identical values, with the exception of the area, volume and lg, due to the fact that in TP_03_B** the spaces in the central part are oriented in a different way.

Table 10 – Numerical result for TP_03_C different aggregative direction

	v	e	A	V	L(g)	PE	p	u	d	gd	lg	η	Θ	β	α	γ	C_{tot}	MST
	(space)	(edges)	(surface)	(volume)	(total leght)	(people)	(sub-cycle)	(cycle)	(diameter)	(density)	(av. leght)						(total cost)	(cost)
TP_03_C*	49	50	643	1930	80	32	1	2	18	0,043	8,63	1,60	0,65	1,02	0,02	0,35	59,5	56,5
TP_03_C**	49	50	580	1741	80	32	1	2	18	0,043	8,65	1,60	0,65	1,02	0,02	0,35	59,5	56,5

TP_04 – “H” type

This experiment analysed the H type distribution, which evolves in only one direction. In this case again the access remains constant, as indicated by the arrow. In the figure below (Figure 45) we can see the cases analysed.

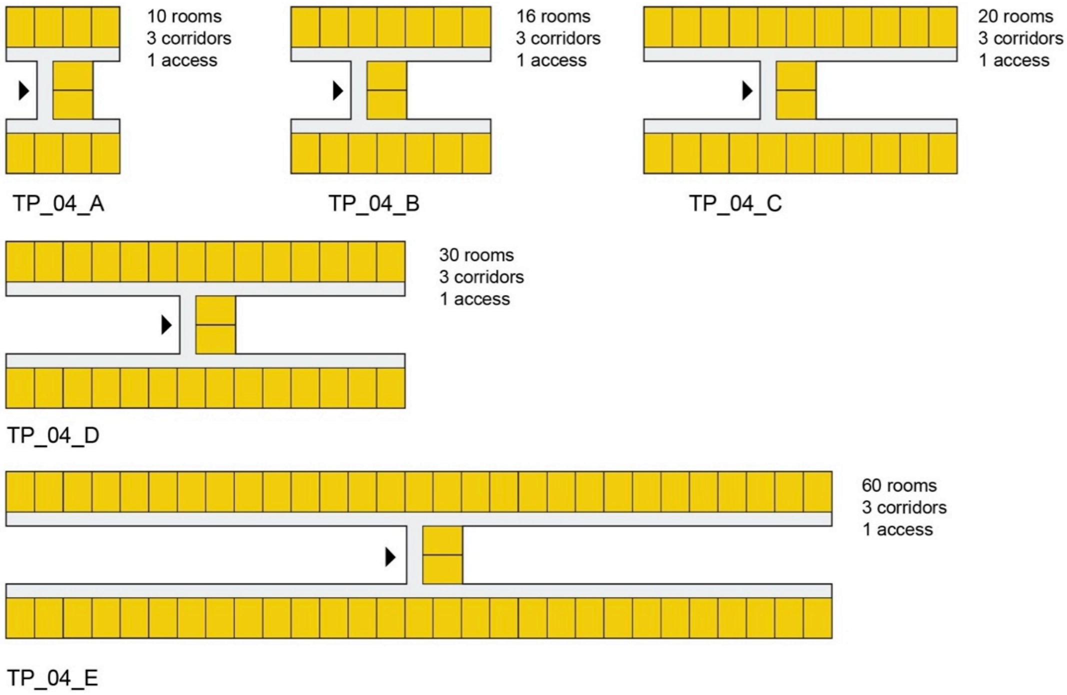


Figure 45 – TP_04

The figure below shows the support structure for the case TP_04_B.

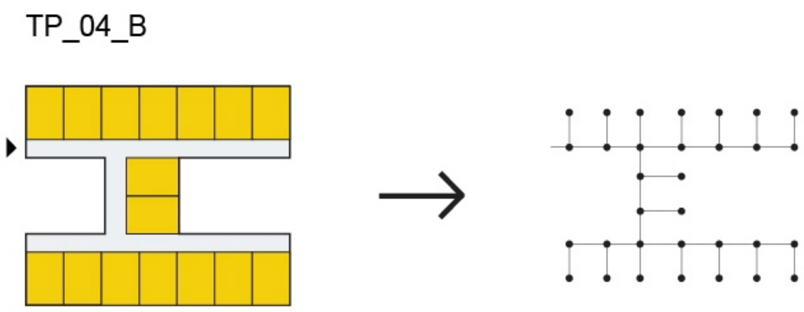


Figure 46 – TP_04_B support structure

The table below (Table 11) shows the numerical results obtained from the analysis.

Table 11 – Numerical result for TP_04

	v (space)	e (edges)	A (surface)	V (volume)	L(g) (total leght)	PE (people)	p (sub-cycle)	u (cycle)	d (diameter)	gd (density)	lg (av. leght)	η	Θ	β	α	γ	C_{tot} (total cost)	MST (cost)
TP_04_A	30	29	353	1061	25	20	1	0	16	0,067	5,92	0,86	0,67	0,97	0,00	0,35	34,5	34,5
TP_04_B	48	47	567	1702	40	32	1	0	24	0,042	8,56	0,85	0,67	0,98	0,00	0,34	55,5	55,5
TP_04_C	72	71	852	2556	50	40	1	0	32	0,028	11,69	0,70	0,56	0,99	0,00	0,34	83,5	83,5
TP_04_D	90	89	1060	3181	75	60	1	0	36	0,022	13,95	0,84	0,67	0,99	0,00	0,34	102,5	102,5
TP_04_E	180	179	2133	6399	150	120	1	0	64	0,110	26,34	0,84	0,67	0,99	0,00	0,34	209,5	209,5

Observing the data achieved and comparing with TP_02, it is possible to see a general increase in η, θ, β and ϒ parameters that assume similar trends.

TP_05 – “T” Type

TP_05 is related to a particular crossing distribution, often occuring in architecture, that is defined as a “T” type distribution. Spaces are added in correspondence on each arm. The access is positioned in correspondence with the vertical axis, as indicated by the arrow. The figure below (Figure 47) presents the cases analysed.

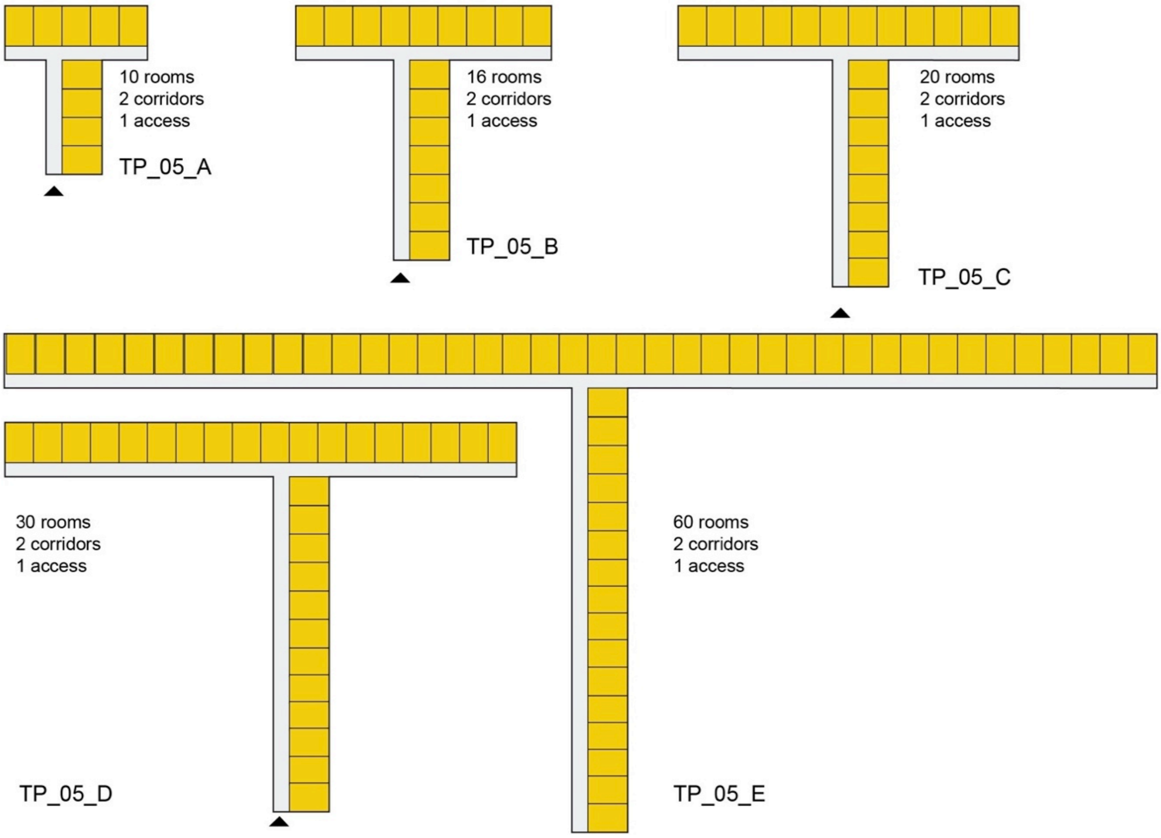


Figure 47 – TP_05

The figure below shows the support structure for the case TP_05_B.

TP_05_B

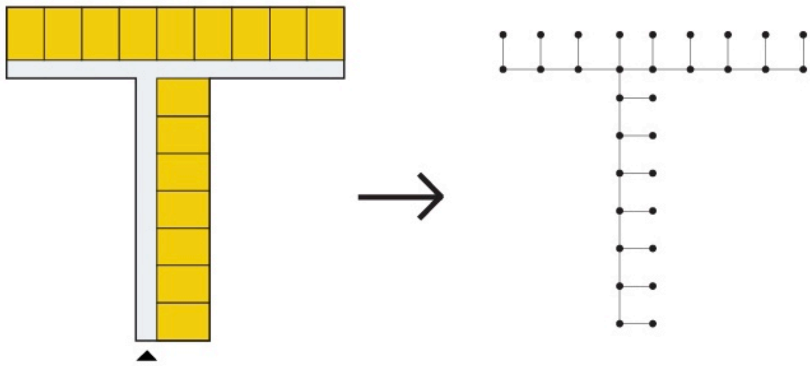


Figure 48 – TP_05_B support structure

The table below (Table 12) shows the numerical results obtained from the analysis.

Table 12 – Numerical result for TP_05

	v (space)	e (edges)	A (surface)	V (volume)	L(g) (total leght)	PE (people)	p (sub-cycle)	u (cycle)	d (diameter)	gd (density)	lg (av. leght)	η	Θ	β	α	γ	C_{tot} (total cost)	MST (cost)
TP_05_A	31	30	352	1056	25	20	1	0	17	0,065	6,66	0,83	0,65	0,97	0,00	0,34	35,5	35,5
TP_05_B	49	48	564	1692	40	32	1	0	25	0,041	9,67	0,83	0,65	0,98	0,00	0,34	56,5	56,5
TP_05_C	61	60	706	2118	50	40	1	0	29	0,033	11,65	0,83	0,66	0,98	0,00	0,34	70,5	70,5
TP_05_D	91	90	1060	3182	75	60	1	0	43	0,022	16,75	0,83	0,66	0,99	0,00	0,34	105,5	105,5
TP_05_E	181	180	2122	6366	150	120	1	0	83	0,011	32,29	0,83	0,66	0,99	0,00	0,34	210,5	210,5

Again in this case, by observing the data achieved and comparing it with TP_02, it is possible to identify a general increase in η, θ, β and ϒ parameters that assume similar trends.

TP_06 – “Circular” type

The circular distribution was the last type analysed. The first three types (A, B and C) have the same diameter and they present only internal modifications, fragmenting the internal spaces as required. Different approaches were applied for cases D and E, which have bigger diameters in order to accommodate double the number of spaces. As with the other cases, the arrow indicates the access. The figure below (Figure 49) shows the cases analysed.

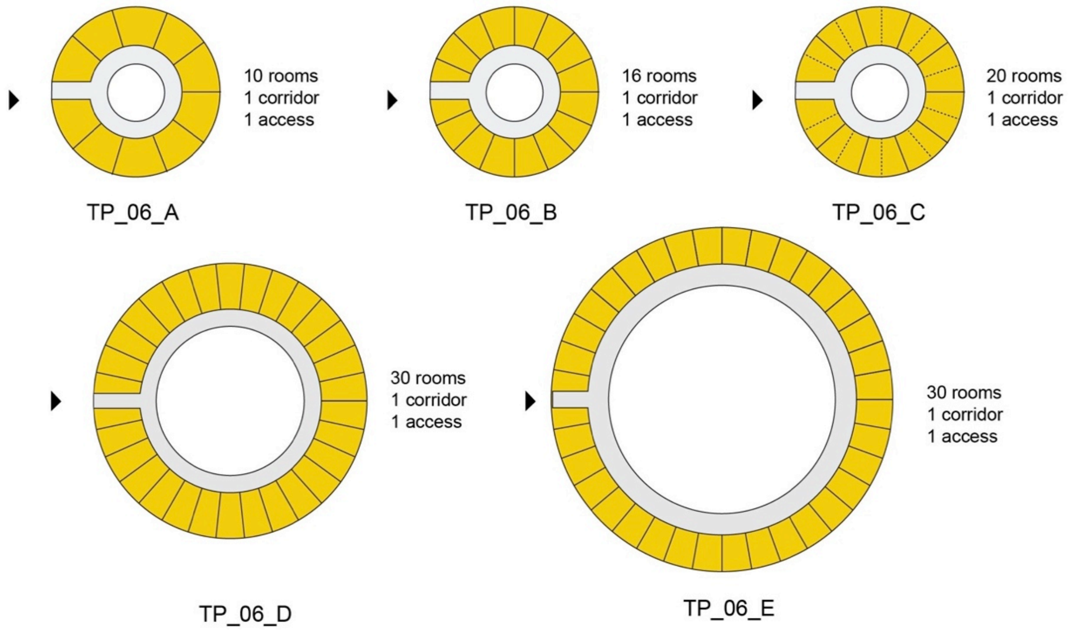


Figure 49 – TP_06

The figure below shows the support structure for the case TP_06_B.

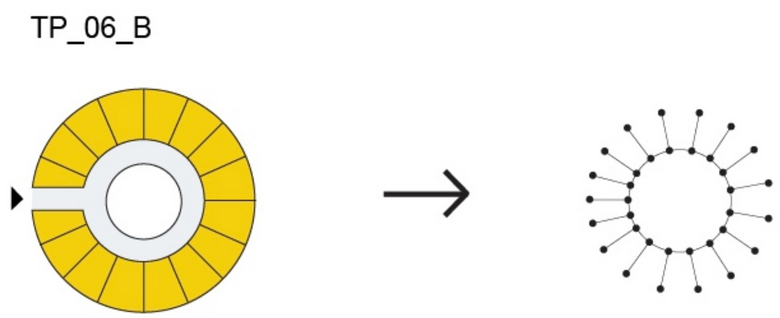


Figure 50 – TP_02_B support structure

The table below (Table 13) shows the numerical results obtained from the analysis.

Table 13 – Numerical result for TP_06

	v (space)	e (edges)	A (surface)	V (volume)	L(g) (total leght)	PE (people)	p (sub-cycle)	u (cycle)	d (diameter)	gd (density)	lg (av. leght)	η	Θ	β	α	γ	C_{tot} (total cost)	MST (cost)
TP_06_A	32	32	545	1635	25	20	1	1	13	0,065	5,87	0,78	0,63	1,00	0,02	0,36	38,5	37,5
TP_06_B	44	44	545	1635	40	32	1	1	16	0,048	7,47	0,91	0,73	1,00	0,01	0,35	53,5	52,5
TP_06_C	50	50	545	1635	50	40	1	1	17	0,041	8,05	1,00	0,80	1,00	0,01	0,35	62,5	61,5
TP_06_D	93	93	981	2945	75	60	1	1	32	0,022	15,43	0,81	0,65	1,00	0,01	0,34	114,5	110,5
TP_06_E	181	181	1729	5183	150	120	1	1	61	0,011	30,35	0,83	0,66	1,00	0,00	0,34	214,5	210,0

Observing the circular distribution and the data achieved, it is possible to establish that η and θ assume similar trends but β and α completely change trend, as shown in Chart 7.

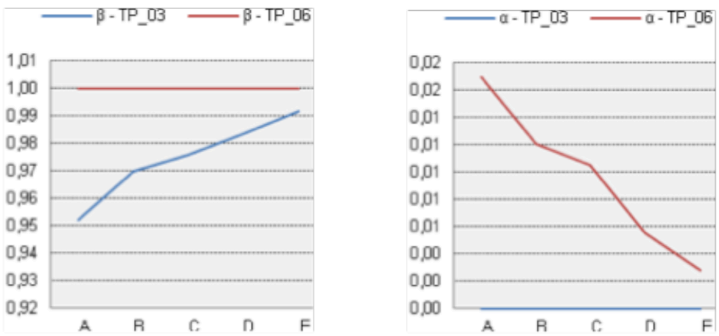


Chart 8 – Comparison between TP_03 and TP_06 for the values of β and α

α has a value due to the fact that a cycle is present, as in the case of TP_03. If we compare this result (TP_06) with TP_03, it is possible to demonstrate that although the two examples have the same number of spaces, TP_03 presents higher values than TP_06, as shown in Chart 8.

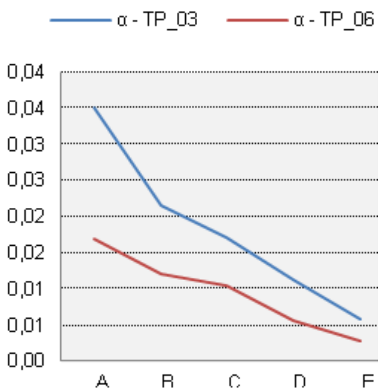


Chart 9 – Comparison between TP_03 and TP_06 for the value of α

TP_07 – Multiple floors (1)

TP_07 studies the behaviour of a building with multiple floors, making particular reference to the position of a vertical core represented by a stair and/or by an elevator. We refer only to an overlapping of the typology TP_02, but a similar approach can also be conducted with the other types. The figures below (Figure 51 and Figure 52) show the cases analysed.

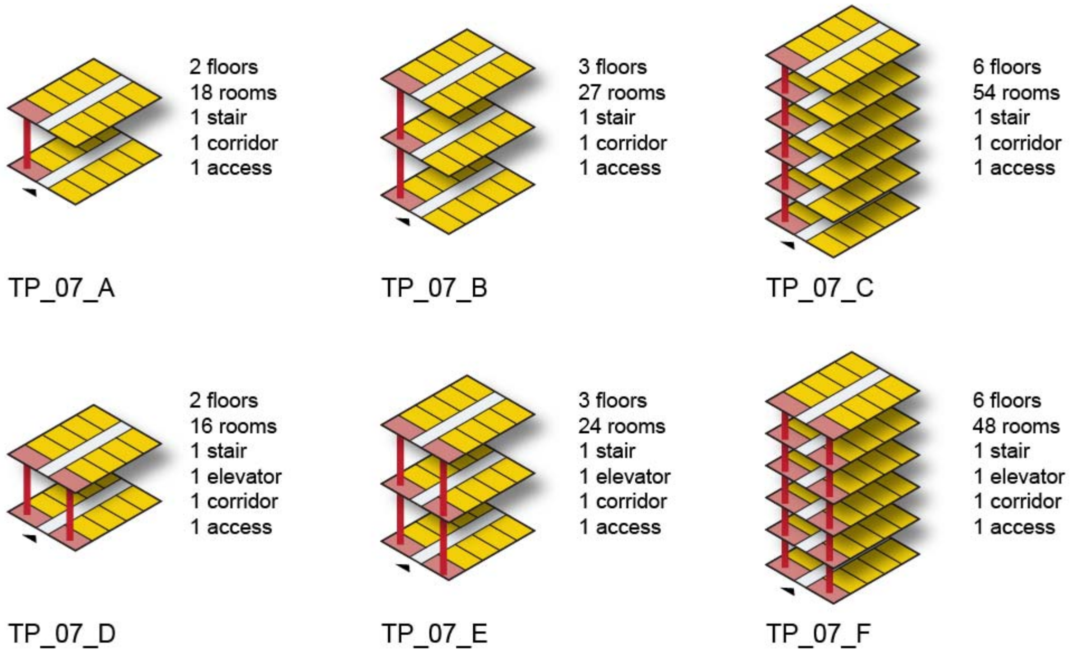


Figure 51 – TP_07a

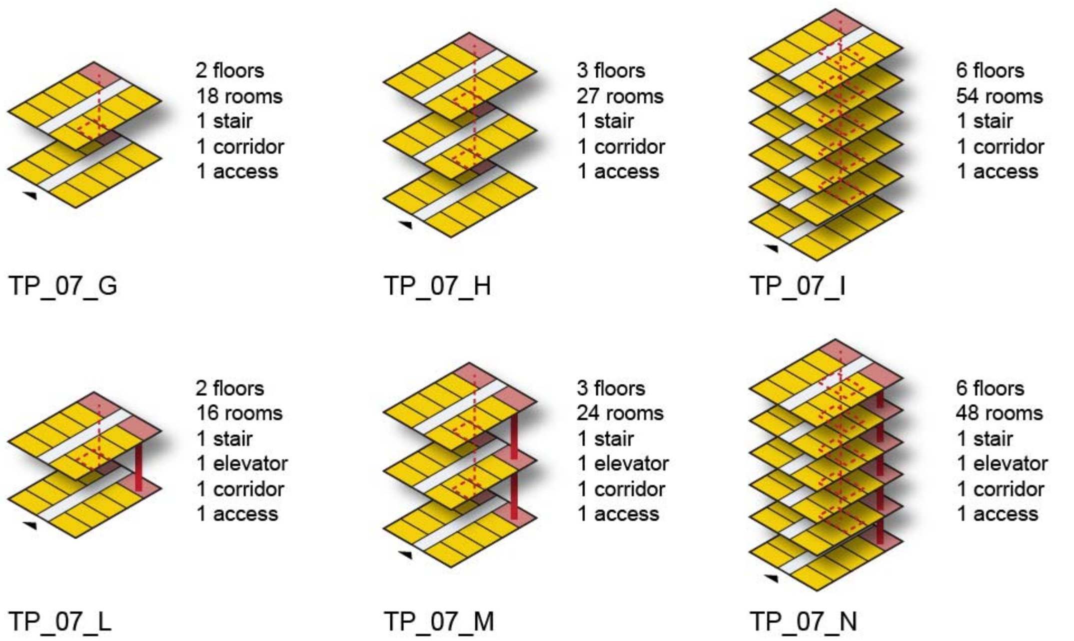


Figure 52 – TP_07b

The following table (Table 14) shows the numerical results obtained from the analysis.

Table 14 – Numerical result for TP_07

	v (space)	e (edges)	A (surface)	V (volume)	L(g) (total leght)	PE (people)	p (sub-cycle)	u (cycle)	d (diameter)	gd (density)	lg (av. leght)	η	Θ	β	α	γ	C_{tot} (total cost)	MST (cost)
TP_07_A	41	40	577	1556	45	36	1	0	23	0,049	8,92	1,13	0,88	0,98	0,00	0,34	52,5	52,5
TP_07_B	61	60	864	2421	67,5	54	1	0	24	0,033	10,57	1,13	0,89	0,98	0,00	0,34	80,0	80,0
TP_07_C	121	120	1729	4755	135	108	1	0	27	0,017	12,89	1,13	0,89	0,99	0,00	0,34	162,5	162,5
TP_07_D	41	43	577	1643	45	36	1	3	21	0,052	7,96	1,05	0,88	1,05	0,04	0,37	55,0	51,0
TP_07_E	61	65	866	2426	67,5	54	1	5	22	0,036	9,29	1,04	0,89	1,07	0,04	0,37	84,5	76,5
TP_07_F	121	131	1729	4755	135	108	1	11	25	0,018	11,30	1,03	0,89	1,08	0,05	0,37	173,0	153,0
TP_07_G	41	42	577	1556	45	36	1	2	20	0,051	7,73	1,07	0,88	1,02	0,03	0,36	52,5	50,5
TP_07_H	61	63	864	2421	67,5	54	1	3	21	0,034	8,95	1,07	0,89	1,03	0,03	0,36	79,0	76,0
TP_07_I	121	126	1729	4755	135	108	1	6	24	0,017	10,81	1,07	0,89	1,04	0,03	0,35	158,5	152,5
TP_07_L	41	43	577	1556	45	36	1	3	20	0,052	7,67	1,05	0,88	1,05	0,04	0,37	53,0	49,0
TP_07_M	61	65	864	2421	67,5	54	1	5	21	0,036	8,88	1,04	0,89	1,07	0,04	0,37	80,5	73,5
TP_07_N	121	131	1729	4755	135	108	1	11	24	0,018	10,72	1,03	0,89	1,08	0,05	0,37	163,0	147,0

The comparison can be performed the considering same number of spaces.

As a first consideration we can analyse the TP_07 in the variation A, D, G and L. As highlighted in Table 14 (in light green) the best value (as expected) for lg is expressed by the solution L that has a stair and an elevator opposite the entrance. The same process can be applied for evaluating the other combinations as shown in Chart 9.

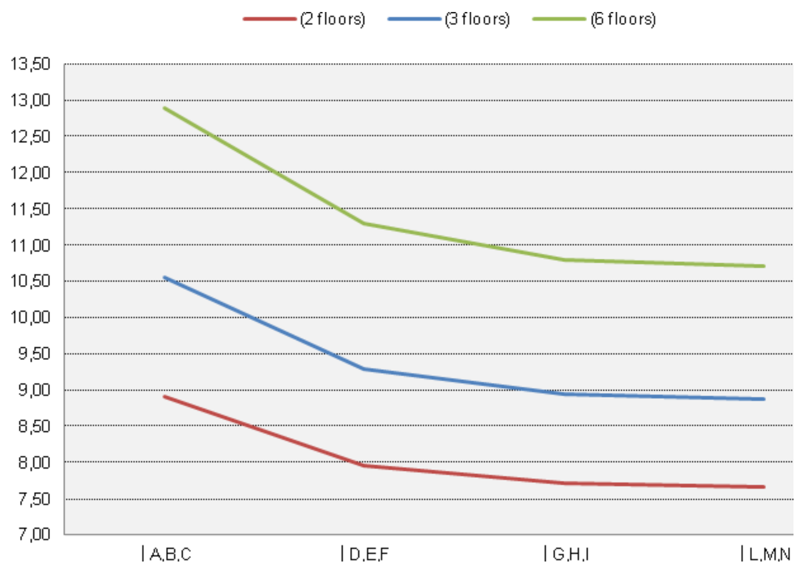


Chart 10 – lg in function of floors and the vertical core position

The result is not surprising because it represents the average shortest path from two remote nodes. On the other hand, however, for architectural reasons it is preferable to place the stairwell or the elevator near the entrances in order to simplify orientation for users and visitors.

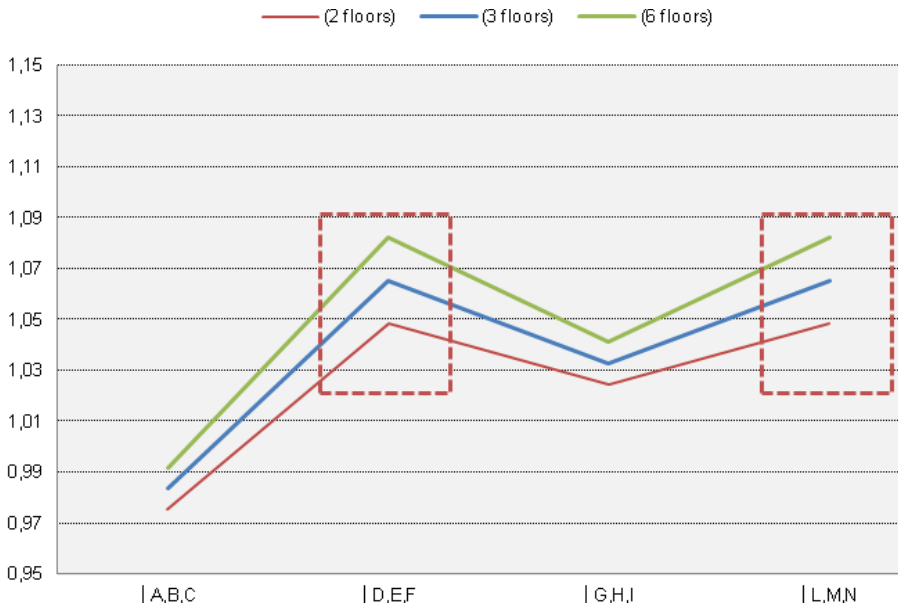


Chart 11 – β in function of floors and the vertical core position

Continuing to examine the parameters, it is possible to highlight a variation of β. If we compare the conditions of only stairs, and the combination of stairs and elevators (A, B, C compared with D, E, F and G, H, I compared with L, M, N) it is possible to observe, as expected, an increase of β if it is added next to the stairs and elevators. In fact solutions D,E,F and L,M,N are the solutions in which an elevator is present.

TP_08 – Multiple floors (2)

In accordance with the method used in TP_07, this case uses the types previously shown (TP_03, TP_04 and TP_05) to assemble multi-floor buildings. This process will be useful in the next chapter, for showing numerical results and the correlation between aggregative shapes and typology. The tiers were overlapped in such a way that the numbers of spaces are comparable with the previous case studies and in particular with the configuration of 30 and 60 spaces.

The figure below (Figure 53) shows the cases analysed.

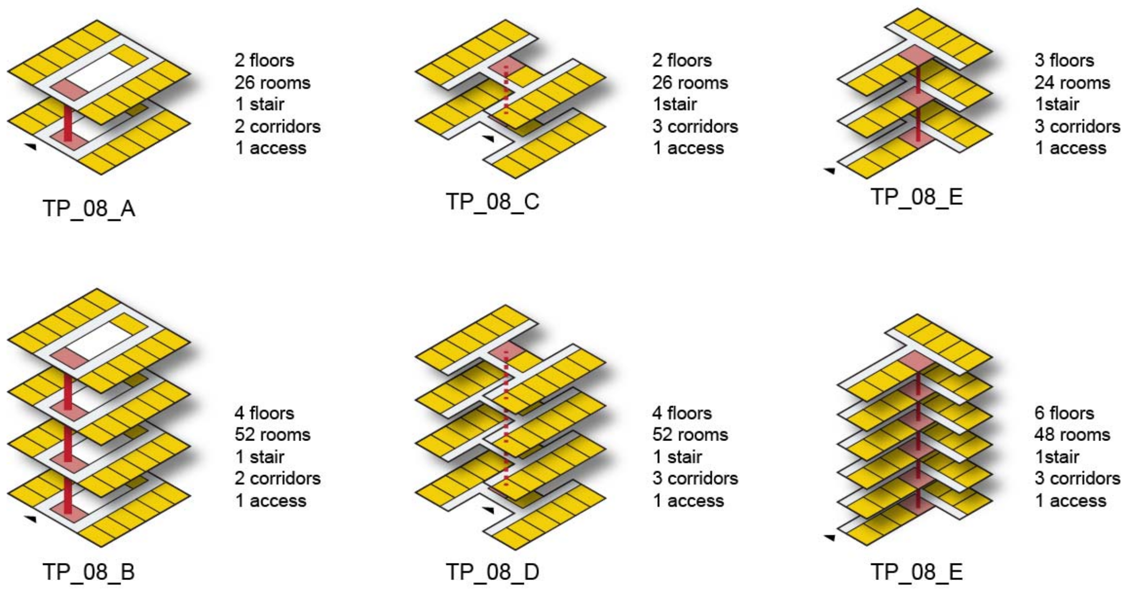


Figure 53 – TP_08

The table below (Table 15) shows the numerical results obtained from the analysis.

Table 15 – Numerical result for TP_08

	v (space)	e (edges)	A (surface)	V (volume)	L(g) (total leght)	PE (people)	p (sub-cycle)	U (cycle)	d (diameter)	gd (density)	lg (av. leght)	η	Θ	β	α	γ	C_{tot} (total cost)	MST (cost)
TP_08_A	71	72	862	2458	65	52	1	2	27	0,029	10,85	0,90	0,73	1,01	0,01	0,35	84,5	82,5
TP_08_B	141	144	1725	4916	130	104	1	4	29	0,015	13,53	0,90	0,74	1,02	0,01	0,35	169,5	165,5
TP_08_C	83	83	994	2834	65	52	1	1	22	0,024	9,55	0,78	0,63	1,00	0,01	0,34	100,0	98,0
TP_08_D	165	164	1990	5522	130	104	1	0	27	0,012	12,10	0,79	0,63	0,99	0,00	0,34	193,5	193,5
TP_08_E	47	46	565	1610	60	48	1	0	17	0,043	7,56	1,30	1,02	0,98	0,00	0,34	54,5	54,5
TP_08_F	93	92	1130	3136	120	96	1	0	19	0,022	9,11	1,30	1,03	0,99	0,00	0,34	109,5	109,5

Moreover, the comparison proceeds by looking at these multiple floor cases together with the other examples previously shown that have similar numbers of spaces. The first analysis (1) will consider a range of spaces from 16 to 20: TP_01_D, TP_01_D*, TP_02_C, TP_03_C, TP_04_C, TP_05_C, TP_07_A, TP_07_D, TP_07_G, TP_07_L, TP_08_A, TP_08_C and TP_08_E as shown in Figure 39.

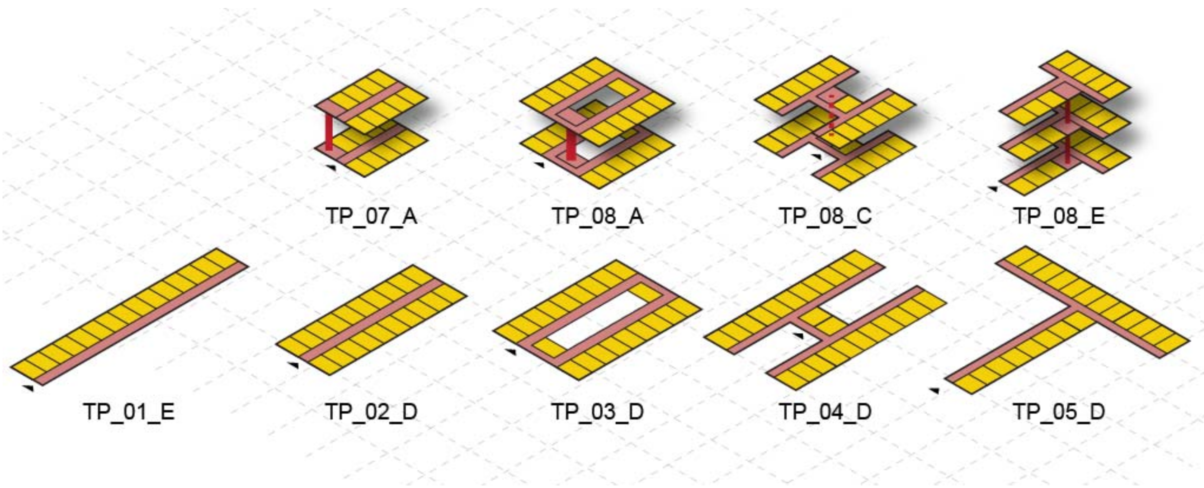


Figure 54 – Comparison between types with similar numbers of spaces

Table 16 – Synthesis of the values for the evaluations

	v (space)	e (edges)	A (surface)	V (volume)	L(g) (total leght)	PE (people)	p (sub-cycle)	u (cycle)	d (diameter)	gd (density)	lg (av. leght)	η	Θ	β	α	Γ	C_{tot} (total cost)	MST (cost)
TP_01_E	91	90	1066	3200	150	60	1	0	61	0,022	21,106	1,67	0,66	0,99	0,00	0,34	105,5	105,5
TP_02_D	61	60	864	2593	75	60	1	0	31	0,033	11,317	1,25	0,98	0,98	0,00	0,34	75,5	75,5
TP_03_D	91	92	1070	3211	150	60	1	2	32	0,022	15,608	1,63	0,66	1,01	0,01	0,34	108,5	105,5
TP_04_D	90	89	1060	3181,8	75	60	1	0	36	0,022	13,952	0,84	0,67	0,99	0,00	0,34	102,5	102,5
TP_05_D	91	90	1060	3182	75	60	1	0	43	0,022	16,746	0,83	0,66	0,99	0,00	0,34	105,5	105,5
TP_07_A	61	60	864	2421	67,5	54	1	0	24	0,033	10,565	1,13	0,89	0,98	0,00	0,34	80,0	80,0
TP_08_A	71	72	862	2458	65	52	1	2	27	0,029	10,845	0,90	0,73	1,01	0,01	0,35	84,5	82,5
TP_08_C	83	83	994	2834	65	52	1	1	22	0,024	9,55	0,78	0,63	1,00	0,01	0,34	100,0	98,0
TP_08_E	47	46	565	1610	60	48	1	0	17	0,043	7,56	1,30	1,02	0,98	0,00	0,34	54,5	54,5

Observing table 16, in which the horizontal line indicates the divide between single floors and multiple floors, it is possible to comment on some values:

- η and θ are indicators of the traffic within the building because η is an indicator of fragmentation of the space while θ is a pure indicator of the internal traffic. If θ is high, the solution may have problems in circulation. The greater this value is, the more the load of the graph showing the traffic between two consecutive nodes per person (or any units that we want to calculate). TP_01_E, according to this definition, seems to be the worst condition.

- Higher value of β indicated better connectivity. There is a slight difference that leads us to indicate TP_03_D and TP_08_A as the best solutions, although the other solutions also have similar values.
- TP_02_D and TP_08_E indicate a more efficient solution in terms of cost of movement.

Discussion of results for “behaviour of parameters”

Through this preliminary survey it has been shown that some parameters noticeably change when a modification of the internal layout distribution is applied. This behaviour is easily visible in the cases that we have analysed, especially regarding the realization of open spaces and the addition of a vertical core, such as in the TP_01*, TP_07 and TP_08 cases.

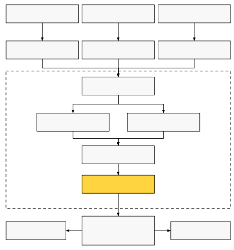
The evaluation can only be performed in cases where the number of spaces is similar because it has been shown that different space numbers give different results in terms of parameters. Cases that have different numbers of spaces are not comparable for evaluating an improvement in terms of connectivity.

A good criterion by which to evaluate a design solution may be observing the variation of parameters as a function of the objective that the designer wants to achieve. For instance, if we would like to find a solution which minimizes the connective distance between spaces, we must reduce the value of Ig and the cost, whilst maximizing parameters such as β and ϒ. On the contrary, if we would like to find a solution in which spaces are spread and distant from each other, we can choose higher values of cost and Ig, and minimize the dimensionless parameter.

Particular consideration has to be paid regarding η and θ. These two values have an important meaning because they are indicators of the traffic within the building. η is an indicator of fragmentation of the space while θ is a pure indicator of the internal traffic. They are subject to the assessments of the traffic provision (in terms of people, flow, material, etc.) that occur within the building. Due to the fact that in this first part of our survey we did not refer to a particular typology, neither did we use a specific method for evaluating the quantity of internal flows within the building. For the above cases we hypothesized a certain number of people for each space (2 for each space).

References to the flow calculation within buildings is addressed more extensively in relation to specific typology (see Chapter 5 – residential villas).

5 Case studies



The aim of the phase of experimentation is to understand the validity of using Graph Theory for layout design and, subsequently, to hypothesize the basis for a possible design method based on mathematical rules. The analyses conducted are based on specific case studies used for calculating the parameters described in Appendix B. The numerical results are given in the following sections. The expected result is a correlation between architectural layout design and graph parameters that can be used to define a method for optimizing connectivity in the re-design project.

The experiments are subdivided into two categories:

1. “Sampling”;
2. Manchester City Library.

The second set of tests, which we have defined as “**sampling**” (2), refer to the analysis of a particular building type. This experiment examines a population of cases (buildings already built or planned) belonging to the same building type. In this case “**residential villas**” were chosen, comparing different masterpieces of architecture in relation to the number of spaces and dimensions (in terms of surface extension and numbers of floors). For each layout distribution the topological graph was extracted and the corresponding parameters were calculated. The aim was to identify those elements that are constantly present in all cases and that can be considered as invariant for this particular building type. Again for these analyses the tools used were Revit, Gelphi, Exel and MatLAB.

The final test, an example of a decision-making process for “**Manchester City Library**” (3), is a simulation of a hypothetical re-design process based on the real life case of the recent redevelopment of Manchester City Library.[193] Reasoning “ad absurdum”, we hypothesized several configurations for the new installation of a vertical connective core. Starting from the initial model, “Survey Model”, five versions of a new design solution were proposed. In this case the Solibrì Model Checker was used in addition to the other tools, in order to verify the consistency of data included in the IFC file.

[193] Particular thanks go to Manchester City Council and the architectural firm Ryder Architecture for providing access to the documentation and the BIM models.

5.1 “Sampling”

“Sampling” is a useful method for approaching a particular typology. It consists of examining a number of existing buildings belonging to the same category of building types that represent good examples of design solutions in particular contexts. The extension of research and the type of analysis to be performed is closely related to the objectives to be pursued and to the level of knowledge that the designer has in relation to the design task. This moment represents the phase of synthesis and it must tend essentially to the identification of those elements that are constantly present in all the case studies analysed, and that can be considered as invariant. These values can be used as a reference model and constitute a set of values for individuating a further design solution which is acceptable. In fact, it is safe to assume that the repetition of a specific design solution involves finding a positive compliance with the latter behavioural needs posed by the users.

Like the method described by Langenhanb et al.,[194] in this work a method was applied to extract the semantic “fingerprints” of buildings. The connectivity graph, as a part of the topology, can be extracted from the building information modelling and represented as graphs. The particular features of the architectural solution are represented by specific quantified parameters. This method can also be used for historical purposes, to understand the evolution of a particular era of design and expression in terms of internal movement.

For this case, it was decided to analyse famous masterpieces of singular residential buildings designed by the masters of architecture that are universally recognized as among the best examples of modern architecture.[195]

The performance reported in the following tables was processed on a scale from 0 to the maximum value of the parameters taken into account (η, Θ, β, α and γ). The value reported was calculated by subdividing the original value with the maximum value in accordance with the following formula:

$$\eta_{performace} = \frac{\eta}{\eta_{max}}$$

[194] Langenhanb et al., 2013.

[195] Weston, 2004; Davis, 2007.

Table 17 – Test on architectural masterpieces

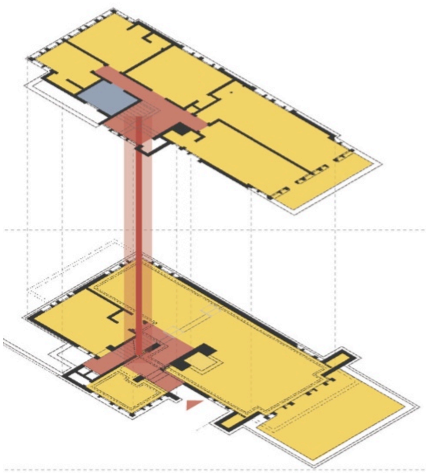
Typology:	Residential[196]				
Sub-category:	Villas				
Code	**Denomination**	**Architect**	**Year**	**City**	**State**
RV 01	Thomas H. Gale House	Frank Lloyd Wright	1904	Oak Park	Illinois (USA)
RV 02	Hill House	Charles Rennie Mackintosh	1904	Helensburg	United Kingdom
RV 03	Villas La Roche-Jeanneret	Le Corbusier	1925	Paris	France
RV 04	Houses Bauhaus' teachers	Walter Gropius	1927	Dessau	Germany
RV 05	Moller's House	Adolf Loos	1928	Wien	Austria
RV 06	Tugendhat's House	Mies Van Der Rohe	1928-30	Brno	Czech Republic
RV 07	Ville Savoye	Le Corbusier	1928-30	Poissy	France
RV 08	Model House	Mies Van Der Rohe	1931	Berlin	Germany
RV 09	Schminke's House	Hans Scharoun	1932-33	Löbau	Germany
RV 10	Villa Mairea	Alvar Aalto	1938-39	Noormarkku	Finland
RV 11	Malaparte's House	Adalberto Libera	1936-40	Capri	Italy
RV 12	House Farnsworth	Mies Van Der Rohe	1945-51	Plano	Illinois (USA)
RV 13	Ulgrade's House	José Antonio Coderch	1952	C. d'Estract	Spain
RV 14	Sperimental House	Alvar Aalto	1952-54	Muuratsalo	Finland
RV 15	Esherick House	Louis Kahn	1961	Philadelphia	Pennsylvania (USA)
RV 16	San Cristòbal	Luis Barragàn	1968	Mexico City	Mexico
RV 17	Fischer House	Louis Kahn	1973	Philadelphia	Pennsylvania (USA)
RV 18	Koshino's House	Tadao Ando	1979-81	Ashiya	Japan
RV 19	Rotunda's House	Mario Botta	1980-82	Stabio	Switzerland
RV 20	Möbius House	UNStudio	1998	Utrecht	Holland

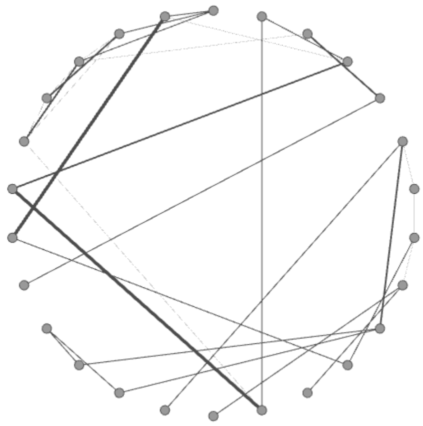
[196] The cases shown in Table 17 are based on the drawings that represent plans, sections and elevations of the architecture published in a series of volumes (Weston, 2004; Davies, 2007; Gregory, 2008) and reported in the Bibliography.

RV_01

Description:

Thomas H. Gale House – Frank Lloyd Wright – 1904 – Oak Park – Illinois (USA)

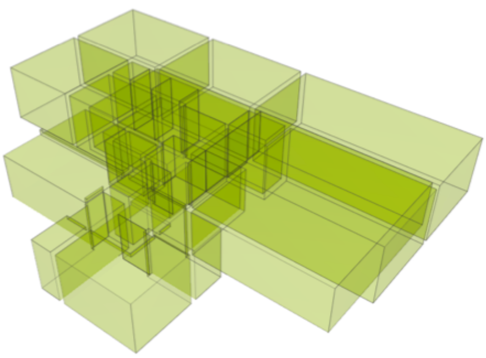


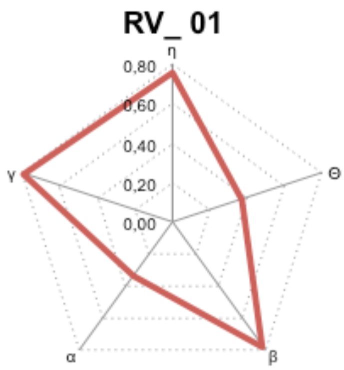


Axonometric | Graph achieved from Gephi

Value:

v	e	A	V	L(g)	PE	p	u	d	g_d	l_g	η	Θ	β	α	γ	C_{tot}	MST
(space)	(edges)	(surface)	(volume)	(total leght)	(people)	(sub-cycle)	(cycle)	(diameter)	(density)	(av. leght)						(total cost)	(cost)
31	33	426	1225	26	7	2	4	8	0,102	4,16	0,79	0,23	1,06	0,07	0,38	49,5	34



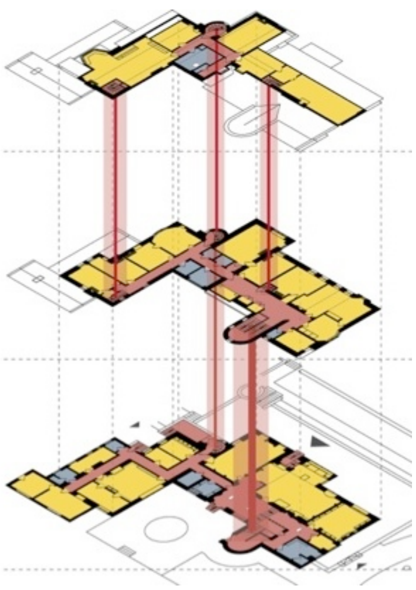


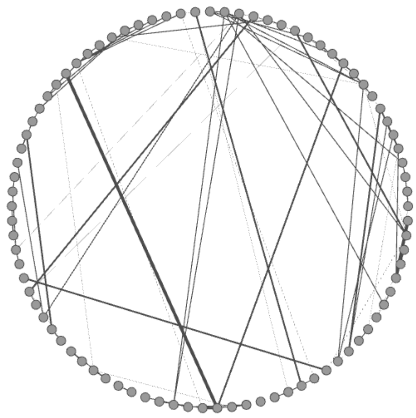
IFC file – X-ray view of the spaces | Performance

RV_02

Description:

Hill House – Charles Rennie Mackintosh – 1904 – Helensburg – United Kingdom

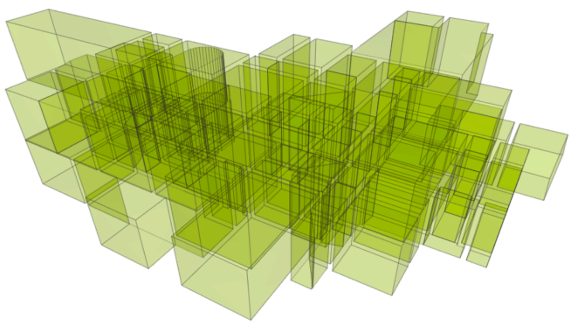


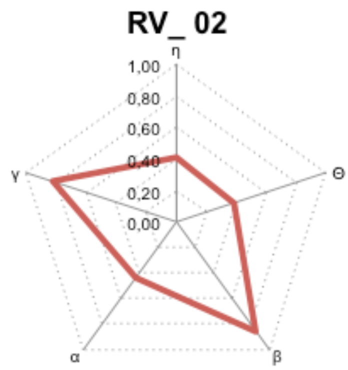


Axonometric | Graph achieved from Gephi

Value:

v	e	A	V	L(g)	PE	p	u	d	g_d	l_g	η	Θ	β	α	γ	C_{tot}	MST
(space)	(edges)	(surface)	(volume)	(total leght)	(people)	(sub-cycle)	(cycle)	(diameter)	(density)	(av. leght)						(total cost)	(cost)
85	99	890	2628	42	20	1	15	14	0,028	6,63	0,42	0,24	1,16	0,09	0,40	142	111



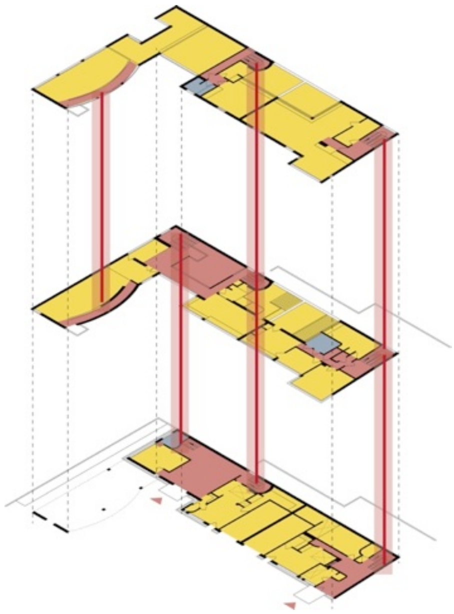


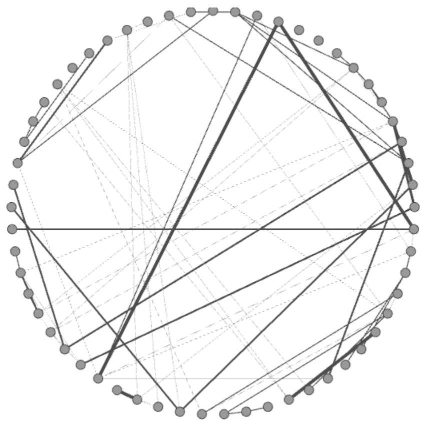
IFC file – X-ray view of the spaces | Performance

RV_03

Description:

Villas La Roche-Jeanneret – Le Corbusier – 1925 – Paris – France

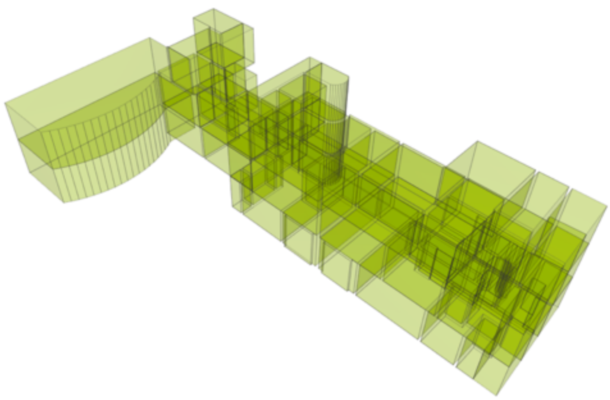


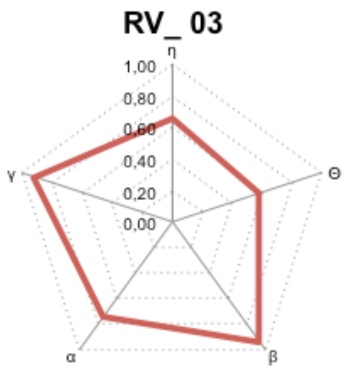


Axonometric | Graph achieved from Gephi

Value:

v (space)	e (edges)	A (surface)	V (volume)	L(g) (total leght)	PE (people)	p (sub-cycle)	u (cycle)	d (diameter)	g_d (density)	I_g (av. leght)	η	Θ	β	α	γ	C_{tot} (total cost)	MST (cost)
57	73	670	2065	50	20	1	17	14	0,05	5,54	0,68	0,35	1,28	0,16	0,44	111	45



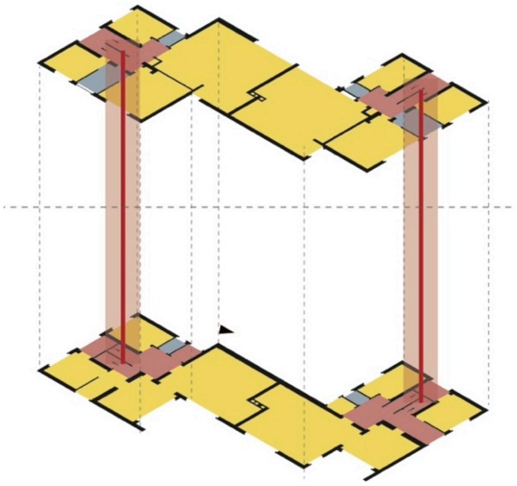


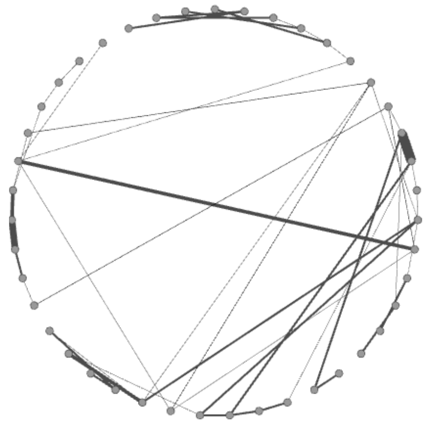
IFC file – X-ray view of the spaces | Performance

RV_04

Description:

Houses for Bauhaus' teachers – Walter Gropius – 1927 – Dessau – Germany

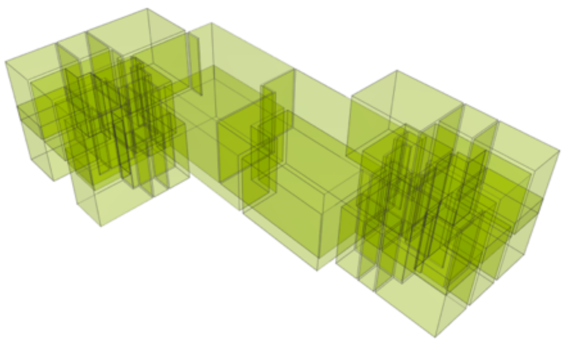


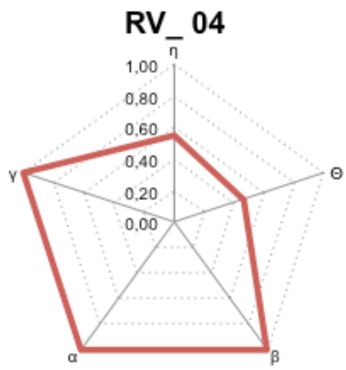


Axonometric	Graph achieved from Gephi

Value:

v (space)	e (edges)	A (surface)	V (volume)	L(g) (total leght)	PE (people)	p (sub-cycle)	u (cycle)	d (diameter)	g_d (density)	l_g (av. leght)	η	Θ	β	α	γ	C_{tot} (total cost)	MST (cost)
57	73	670	2065	50	20	1	17	14	0,05	5,54	0,68	0,35	1,28	0,16	0,44	111	45



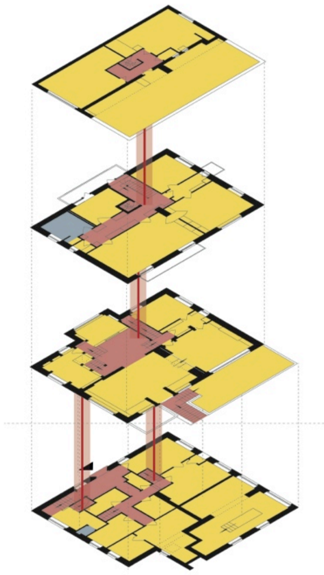


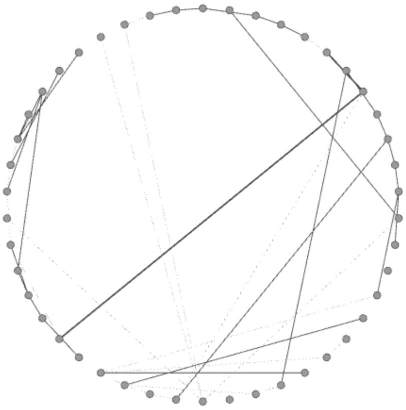
IFC file – X-ray view of the spaces	Performance

RV_05

Description:

Moller's House – Adolf Loos – 1928 – Wien – Austria

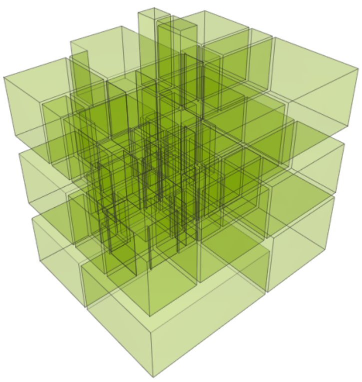


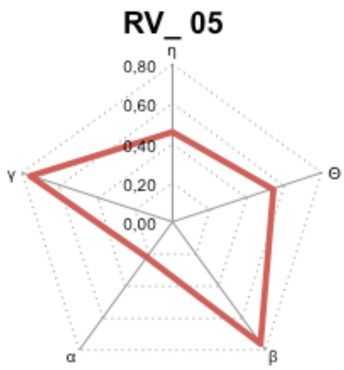


Axonometric | Graph achieved from Gephi

Value:

v	e	A	V	L(g)	PE	p	u	d	g_d	l_g	η	Θ	β	α	γ	C_{tot}	MST
(space)	(edges)	(surface)	(volume)	(total leght)	(people)	(sub-cycle)	(cycle)	(diameter)	(density)	(av. leght)						(total cost)	(cost)
46	48	932	2780	23	15	2	4	12	0,047	6,28	0,48	0,33	1,04	0,05	0,36	64,0	56,5



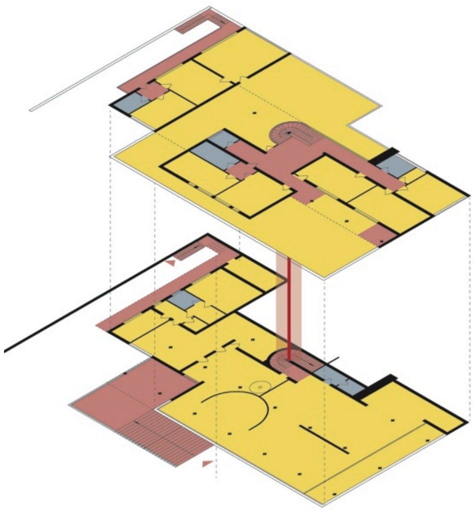


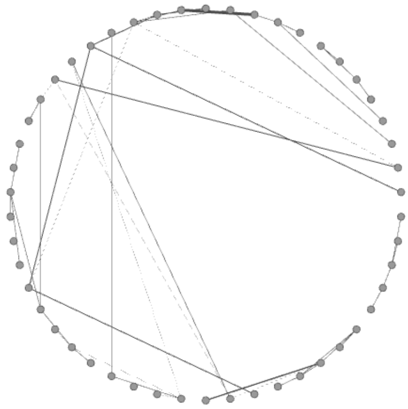
IFC file – X-ray view of the spaces | Performance

RV_06

Description:

Tugendhat’s House – Mies Van Der Rohe – 1928 – Brno – Czech Republic

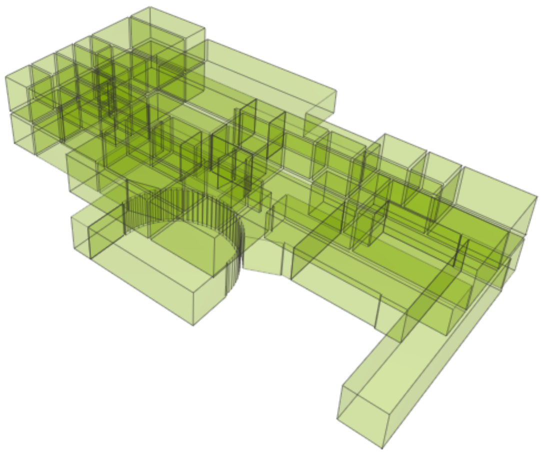


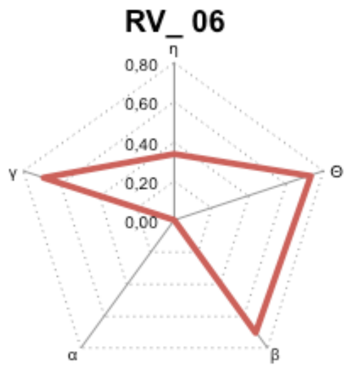


Axonometric	Graph achieved from Gephi

Value:

v	e	A	V	L(g)	PE	p	u	d	g_d	l_g	η	Θ	β	α	γ	C_{tot}	MST
(space)	(edges)	(surface)	(volume)	(total leght)	(people)	(sub-cycle)	(cycle)	(diameter)	(density)	(av. leght)						(total cost)	(cost)
50	48	978	2674	17	22	2	0	11	0,039	5,13	0,35	0,44	0,96	0,00	0,33	73,5	56,0



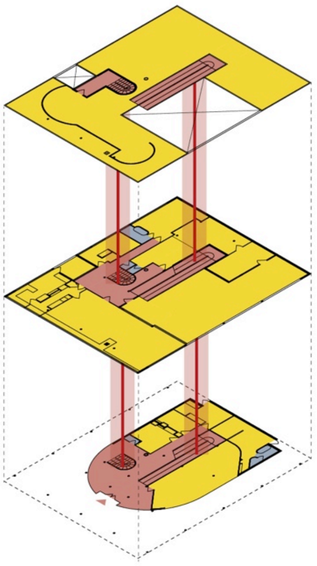


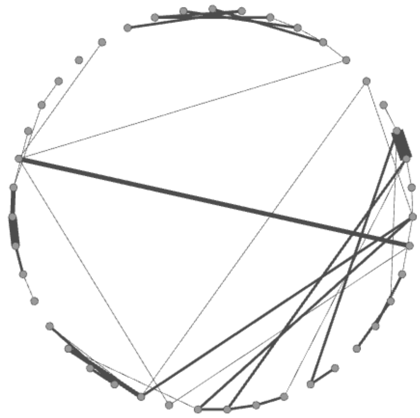
IFC file – X-ray view of the spaces	Performance

RV_07

Description:

Savoye's Villa – Le Corbusier – 1928 – Poissy – France

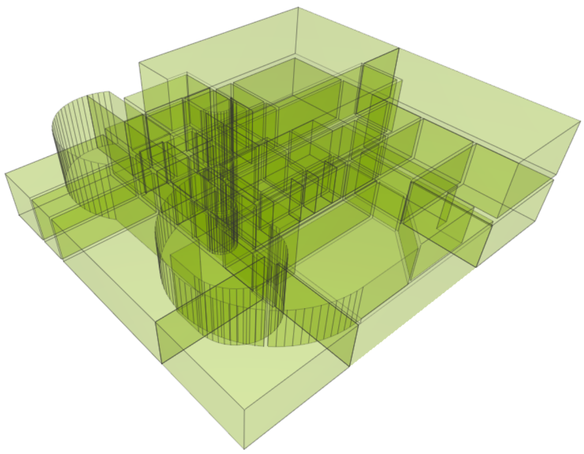


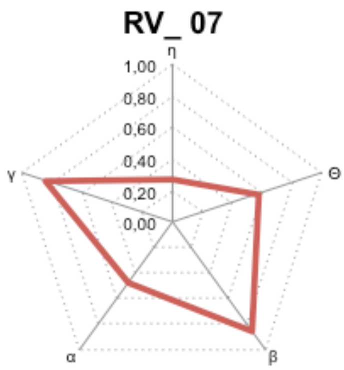


Axonometric	Graph achieved from Gephi

Value:

v	e	A	V	L(g)	PE	p	u	d	g_d	l_g	η	Θ	β	α	γ	C_{tot}	MST
(space)	(edges)	(surface)	(volume)	(total leght)	(people)	(sub-cycle)	(cycle)	(diameter)	(density)	(av. leght)						(total cost)	(cost)
43	50	870	2278	14	15	1	8	14	0,055	5,44	0,28	0,35	1,16	0,10	0,41	61	27



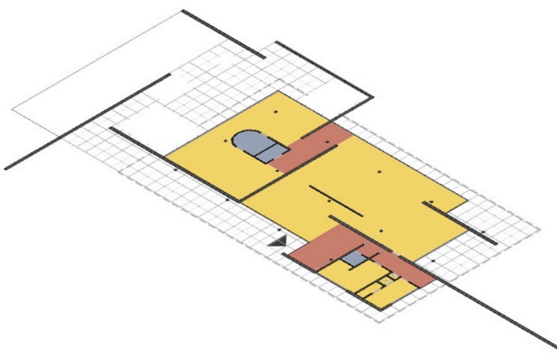


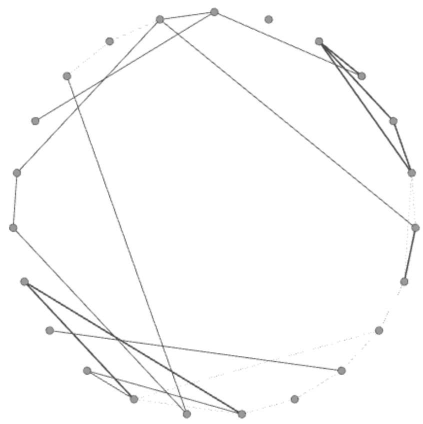
IFC file – X-ray view of the spaces	Performance

RV_08

Description:

Model House – Berlin Exposition – Mies Van Der Rohe – 1931 – Berlin - Germany



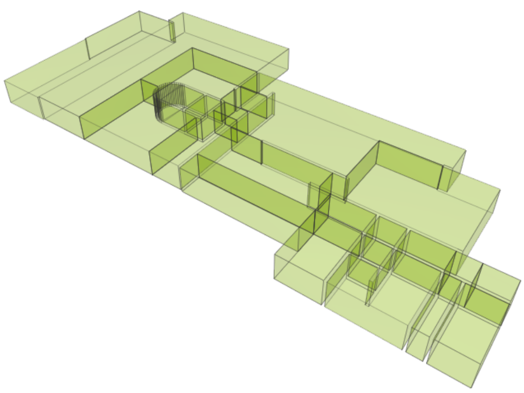


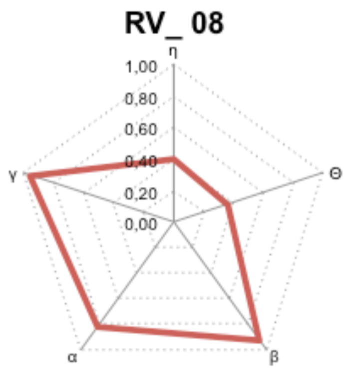
Axonometric

Graph achieved from Gephi

Value:

v	e	A	V	L(g)	PE	p	u	d	g_d	l_g	η	Θ	β	α	γ	C_{tot}	MST
(space)	(edges)	(surface)	(volume)	(total leght)	(people)	(sub-cycle)	(cycle)	(diameter)	(density)	(av. leght)						(total cost)	(cost)
23	29	275	970	12	5	1	7	8	0,115	3,65	0,41	0,22	1,26	0,17	0,46	41,5	27,5





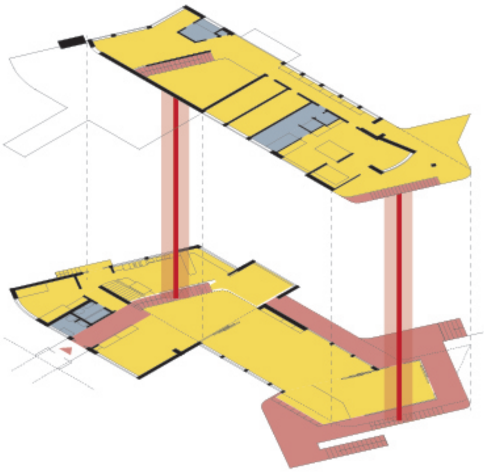
IFC file – X-ray view of the spaces

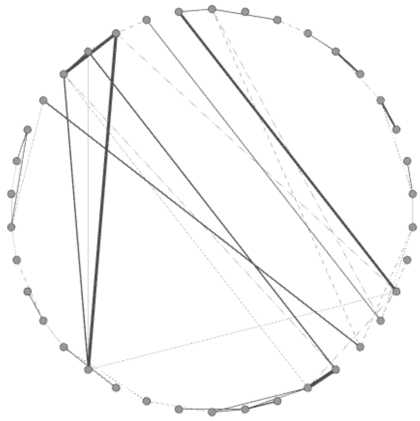
Performance

RV_09

Description:

Schminke's House – Hans Scharoun – 1932 – Löbau – Germany

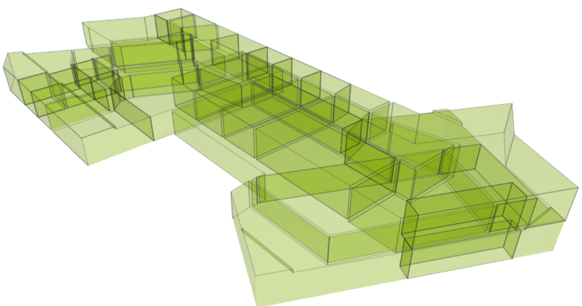


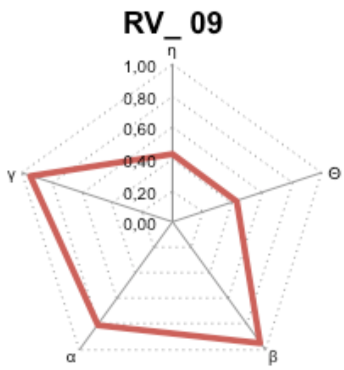


Axonometric | Graph achieved from Gephi

Value:

v (space)	e (edges)	A (surface)	V (volume)	L(g) (total leght)	PE (people)	p (sub-cycle)	u (cycle)	d (diameter)	g_d (density)	l_g (av. leght)	η	Θ	β	α	γ	C_{tot} (total cost)	MST (cost)
38	49	1228	3319	22	10	1	12	11	0,07	4,793	0,45	0,26	1,29	0,17	0,45	73,5	45



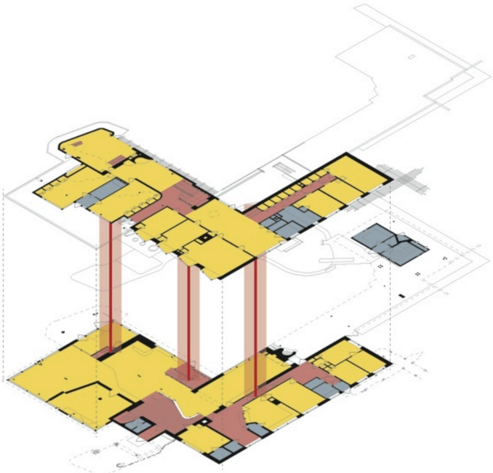


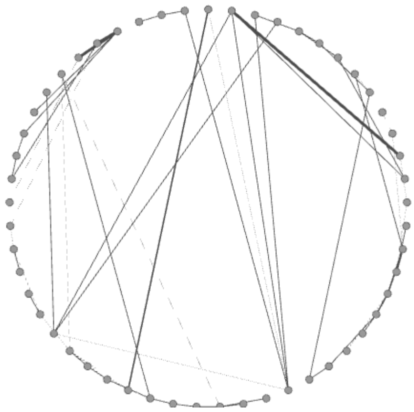
IFC file – X-ray view of the spaces | Performance

RV_10

Description:

Villa Mairea – Alvar Aalto – 1938 – Noormarkku – Finland

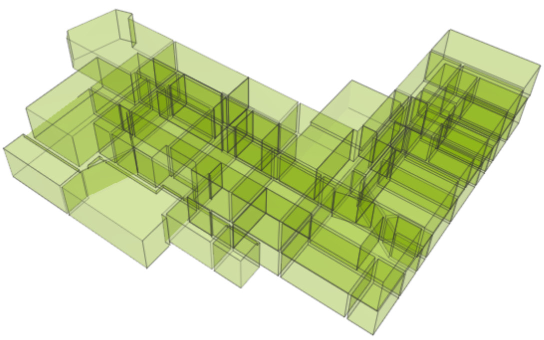


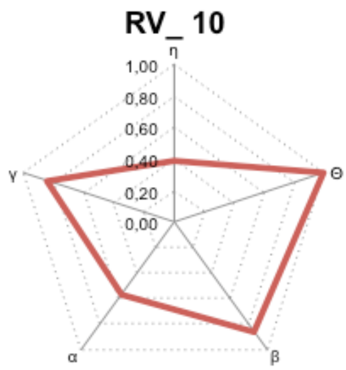


Axonometric	Graph achieved from Gephi

Value:

v	e	A	V	L(g)	PE	p	u	d	g_d	l_g	η	Θ	β	α	γ	C_{tot}	MST
(space)	(edges)	(surface)	(volume)	(total leght)	(people)	(sub-cycle)	(cycle)	(diameter)	(density)	(av. leght)						(total cost)	(cost)
53	62	797	2282	25	32	3	12	17	0,045	6,88	0,40	0,60	1,17	0,12	0,41	90,0	71,0



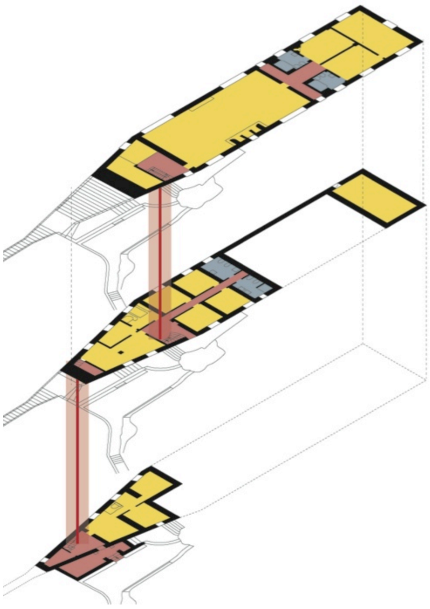


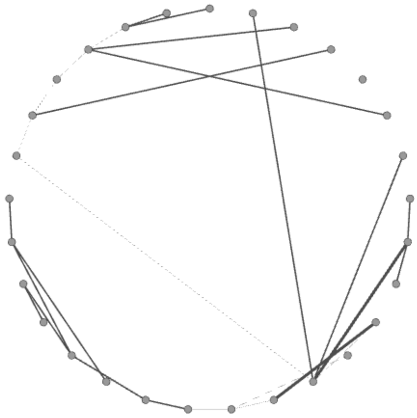
IFC file – X-ray view of the spaces	Performance

RV_11

Description:

Malaparte's House – Adalberto Libera – 1936 – Capri – Italy

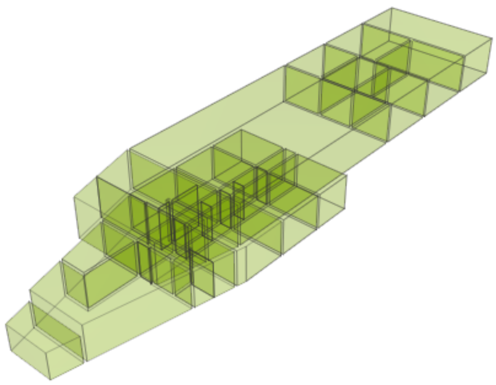


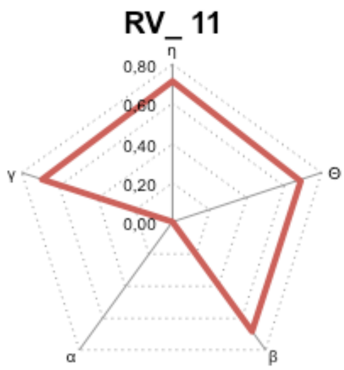


Axonometric	Graph achieved from Gephi

Value:

v	e	A	V	L(g)	PE	p	u	d	g_d	l_g	η	Θ	β	α	γ	C_{tot}	MST
(space)	(edges)	(surface)	(volume)	(total leght)	(people)	(sub-cycle)	(cycle)	(diameter)	(density)	(av. leght)						(total cost)	(cost)
29	27	476	1374	20	12	2	0	14	0,067	5,97	0,74	0,41	0,93	0,00	0,33	37,0	37,0



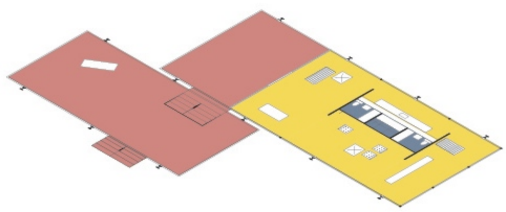


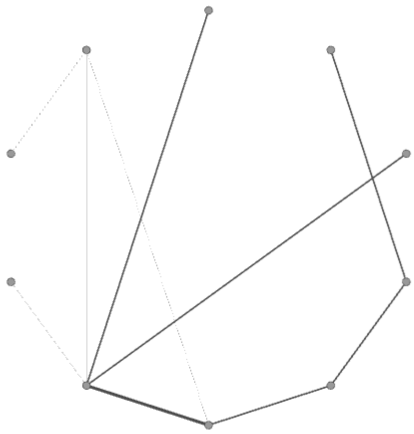
IFC file – X-ray view of the spaces	Performance

RV_12

Description:

House Farnsworth – Mies Van Der Rohe – 1945 – Plano – Illinois (USA)

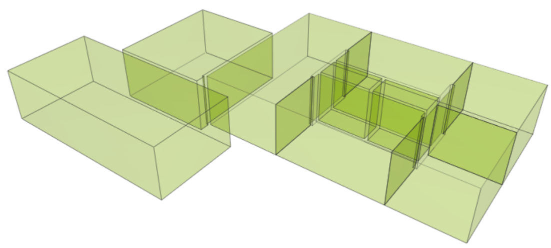


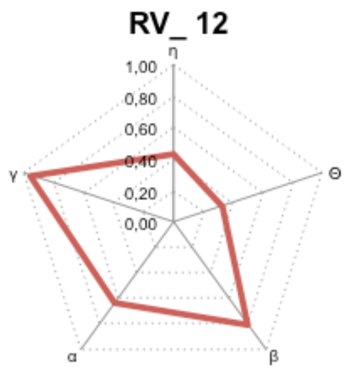


Axonometric | Graph achieved from Gephi

Value:

v	e	A	V	L(g)	PE	p	u	d	g_d	l_g	η	Θ	β	α	γ	C_{tot}	MST
(space)	(edges)	(surface)	(volume)	(total leght)	(people)	(sub-cycle)	(cycle)	(diameter)	(density)	(av. leght)						(total cost)	(cost)
10	11	152	335	5	2	1	2	5	0,244	2,49	0,45	0,20	1,10	0,13	0,46	14,5	11,5



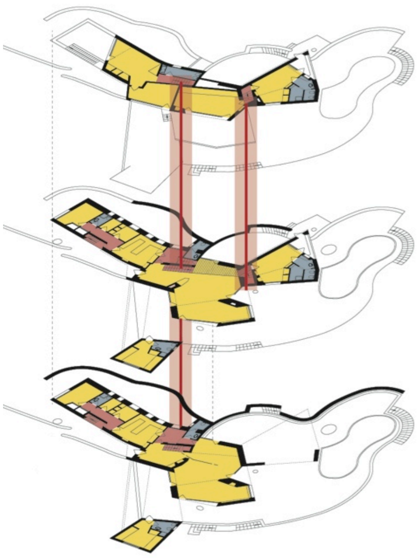


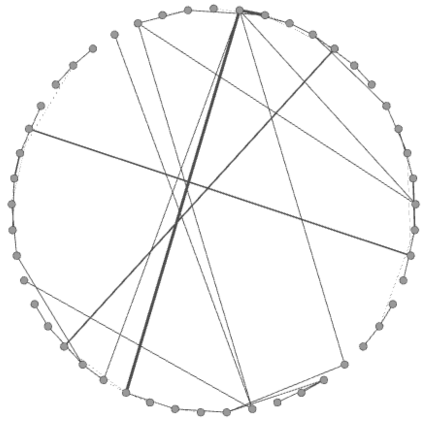
IFC file – X-ray view of the spaces | Performance

RV_13

Description:

Ulgrade's House – José Antonio Coderech – 1952 – C. d'Estract - Spain

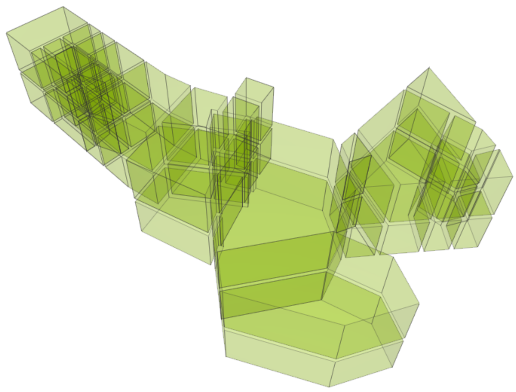


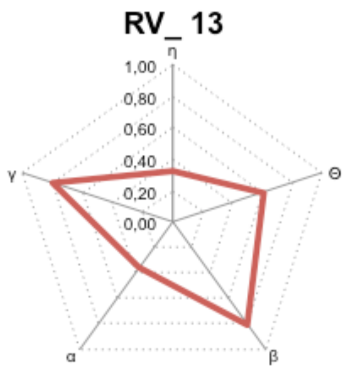


Axonometric | Graph achieved from Gephi

Value:

v	e	A	V	L(g)	PE	p	u	d	g_d	l_g	η	Θ	β	α	γ	C_{tot}	MST
(space)	(edges)	(surface)	(volume)	(total leght)	(people)	(sub-cycle)	(cycle)	(diameter)	(density)	(av. leght)						(total cost)	(cost)
49	54	362	1031	18	18	2	7	12	0,046	5,844	0,33	0,37	1,10	0,08	0,38	79,0	66,0



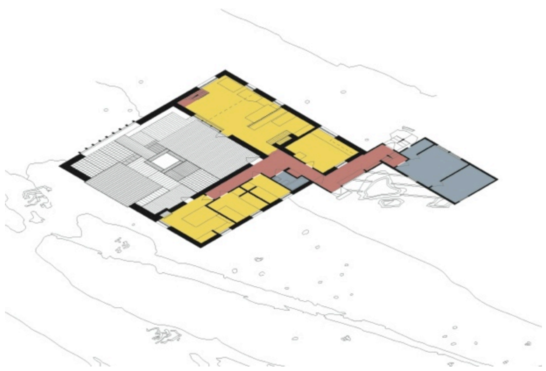


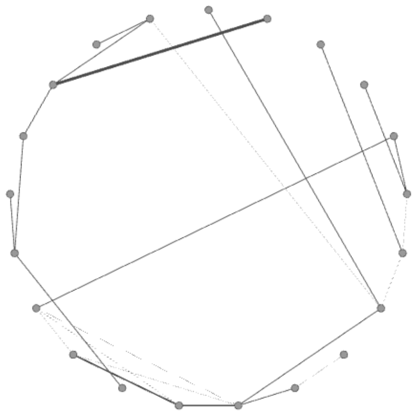
IFC file – X-ray view of the spaces | Performance

RV_14

Description:

Sperimental House – Alvar Aalto – 1952 – Muuratsalo – Finland

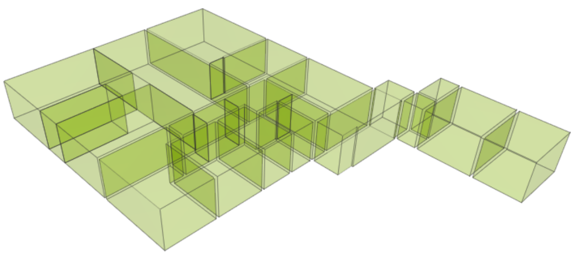


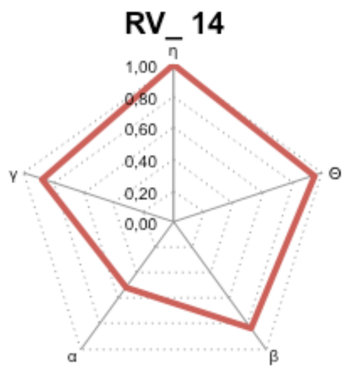


Axonometric	Graph achieved from Gephi

Value:

v	e	A	V	L(g)	PE	p	u	d	g_d	l_g	η	Θ	β	α	γ	C_{tot}	MST
(space)	(edges)	(surface)	(volume)	(total leght)	(people)	(sub-cycle)	(cycle)	(diameter)	(density)	(av. leght)						(total cost)	(cost)
21	24	340	1024	25	12	1	4	8	0,114	3,767	1,04	0,57	1,14	0,11	0,42	34,0	25,0



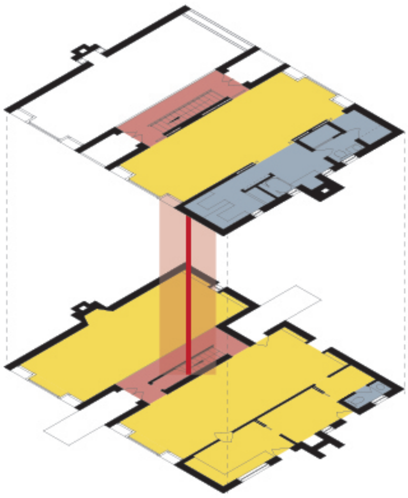


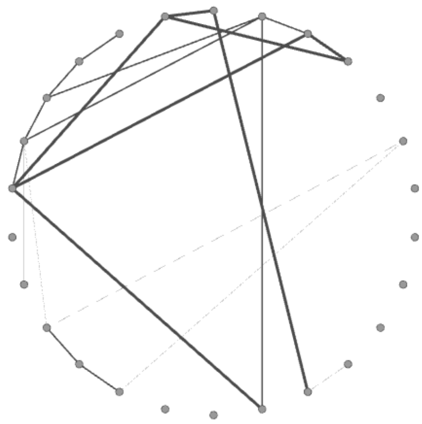
IFC file – X-ray view of the spaces	Performance

RV_15

Description:

Esherick House – Louis Kahn – 1961 – Philadelphia – Pennsylvania (USA)

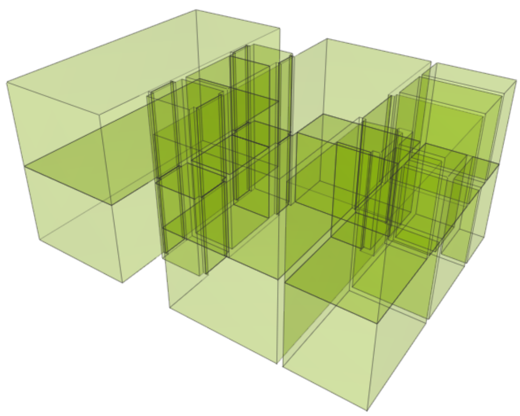


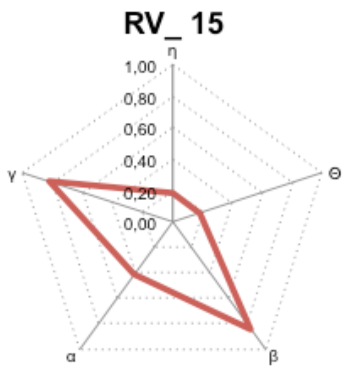


Axonometric	Graph achieved from Gephi

Value:

v (space)	e (edges)	A (surface)	V (volume)	L(g) (total leght)	PE (people)	p (sub-cycle)	u (cycle)	d (diameter)	g_d (density)	l_g (av. leght)	η	Θ	β	α	γ	C_{tot} (total cost)	MST (cost)
55	63	209	629	12	6	0	8	8	0,068	3,386	0,19	0,11	1,15	0,08	0,40	34,0	25,0



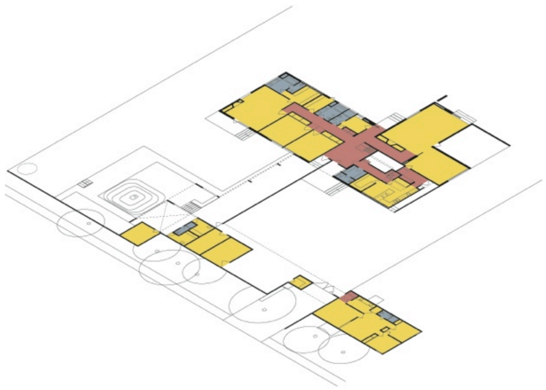


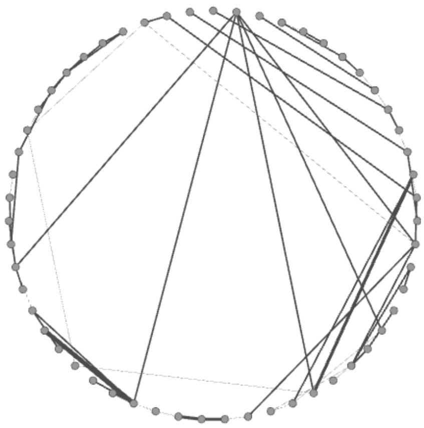
IFC file – X-ray view of the spaces	Performance

RV_16

Description:

San Cristòbal – Luis Barragàn – 1968 – Mexico City - Mexico

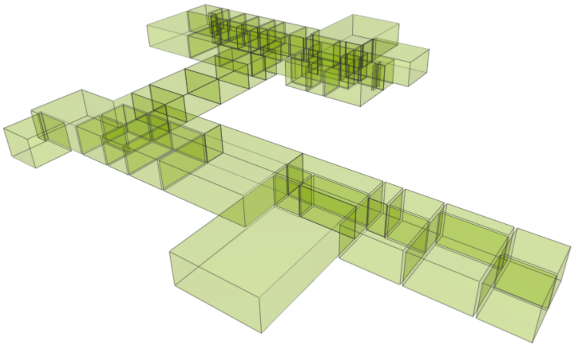


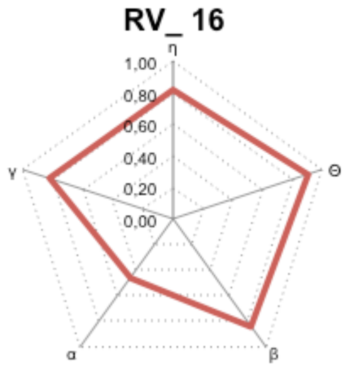


Axonometric | Graph achieved from Gephi

Value:

v	e	A	V	L(g)	PE	p	u	d	g_d	l_g	η	Θ	β	α	γ	C_{tot}	MST
(space)	(edges)	(surface)	(volume)	(total leght)	(people)	(sub-cycle)	(cycle)	(diameter)	(density)	(av. leght)						(total cost)	(cost)
55	63	882	2647	54	30	2	10	16	0,042	5,636	0,86	0,55	1,15	0,10	0,40	86,5	72,0



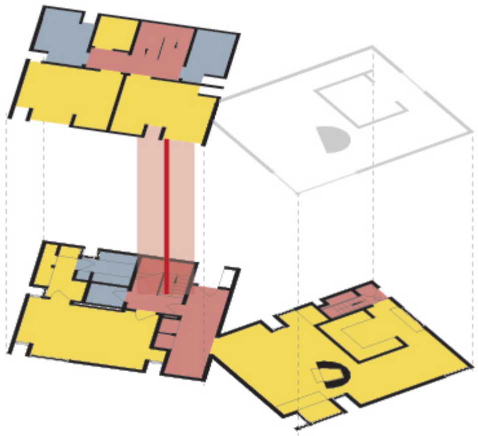


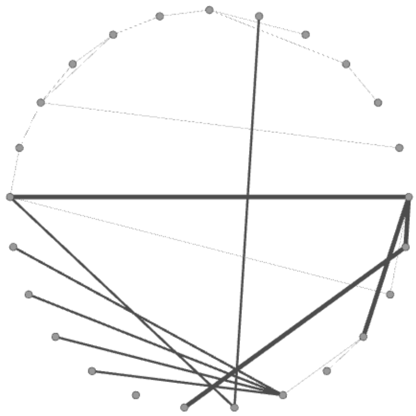
IFC file – X-ray view of the spaces | Performance

RV_17

Description:

Fischer House - Lois Kahn – 1973 – Philadelphia – Pennsylvania (USA)

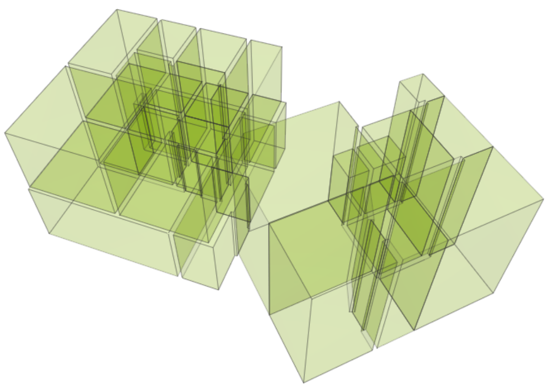


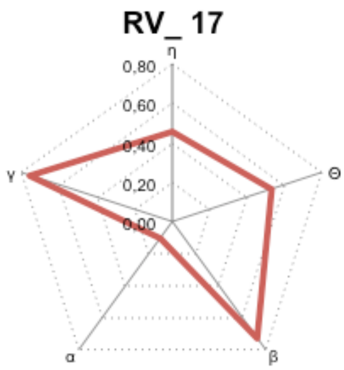


Axonometric | Graph achieved from Gephi

Value:

v	e	A	V	L(g)	PE	p	u	d	g_d	I_g	η	Θ	β	α	γ	C_{tot}	MST
(space)	(edges)	(surface)	(volume)	(total leght)	(people)	(sub-cycle)	(cycle)	(diameter)	(density)	(av. leght)						(total cost)	(cost)
25	25	356	850	12	8	0	0	11	0,083	4,73	0,48	0,32	1,00	0,00	0,36	32,0	29,0



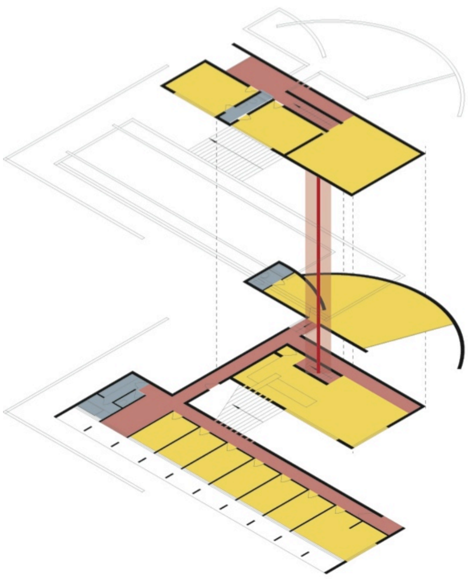


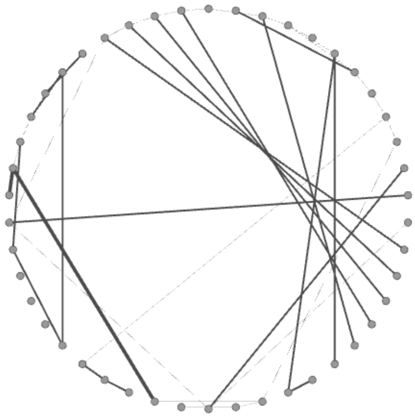
IFC file – X-ray view of the spaces | Performance

RV_18

Description:

Koshino's House – Tadao Ando – 1979 – Ashiya – Japan

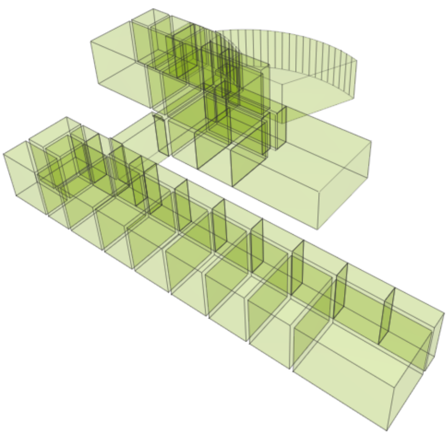


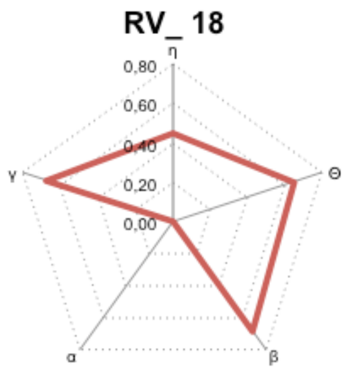


Axonometric | Graph achieved from Gephi

Value:

v	e	A	V	L(g)	PE	p	u	d	g_d	l_g	η	Θ	β	α	γ	C_{tot}	MST
(space)	(edges)	(surface)	(volume)	(total leght)	(people)	(sub-cycle)	(cycle)	(diameter)	(density)	(av. leght)						(total cost)	(cost)
46	43	780	1305	20	18	1	0	20	0,042	7,85	0,47	0,39	0,93	0,00	0,33	54,0	52,5



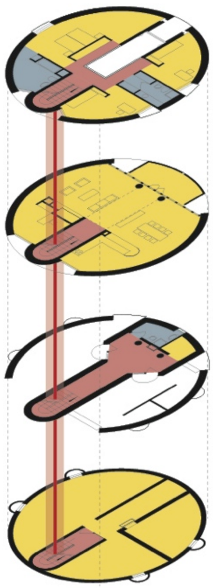


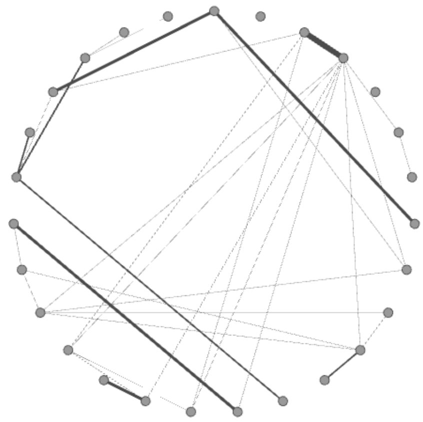
IFC file – X-ray view of the spaces | Performance

RV_19

Description:

Rotunda's House – Mario Botta – 1980 – Stabio – Switzerland

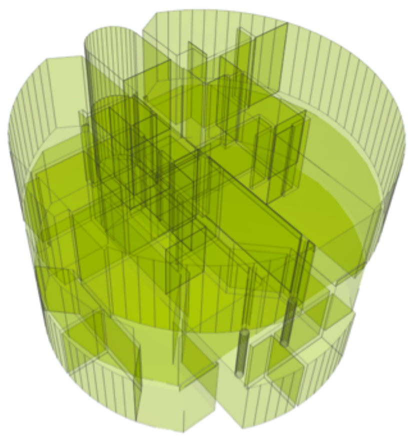


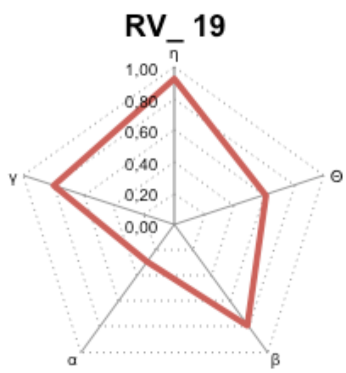


Axonometric | Graph achieved from Gephi

Value:

v (space)	e (edges)	A (surface)	V (volume)	L(g) (total leght)	PE (people)	p (sub-cycle)	u (cycle)	d (diameter)	g_d (density)	I_g (av. leght)	η	Θ	β	α	γ	C_{tot} (total cost)	MST (cost)
27	29	273	771	28	10	1	3	7	0.10	3,40	0,97	0,37	1,07	0,06	0,39	76,5	49



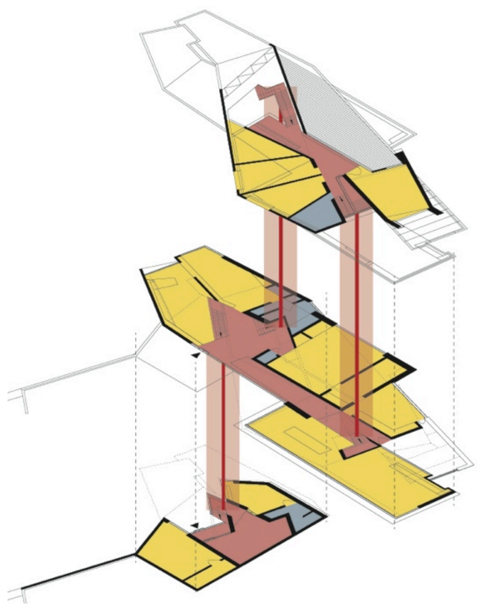


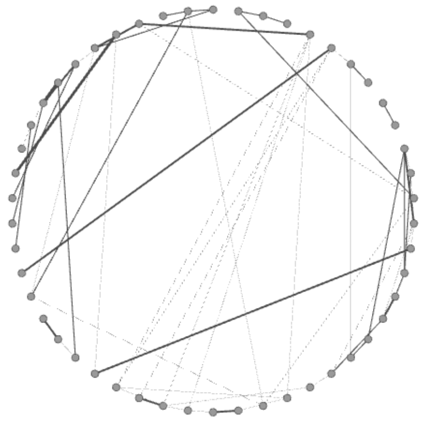
IFC file – X-ray view of the spaces | Performance

RV_20

Description:

Möbious House – UNStudio – 1998 – Utrecht - Holland

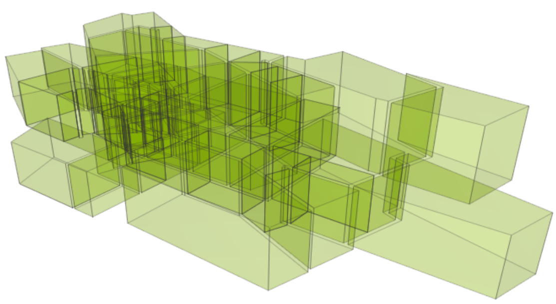


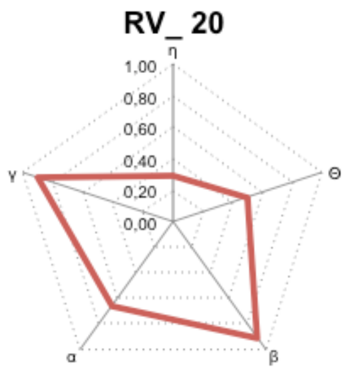


Axonometric | Graph achieved from Gephi

Value:

v	e	A	V	L(g)	PE	p	u	d	g_d	l_g	η	Θ	β	α	γ	C_{tot}	MST
(space)	(edges)	(surface)	(volume)	(total leght)	(people)	(sub-cycle)	(cycle)	(diameter)	(density)	(av. leght)						(total cost)	(cost)
50	62	503	1407	19	15	1	13	15	0,051	5,89	0,30	0,30	1,24	0,14	0,43	85	61





IFC file – X-ray view of the spaces | Performance

5.1.1 Discussion of results for “sampling”

The analysis was performed by comparing cases that were similar in terms of number of spaces and volume. The table below presents the results: red indicates the highest values reported and yellow the lowest, over the 20 case studies.

Table 18 – Comparison of results for “Sampling”

Code		v	e	A	V	L(g)	PE	p	u	d	gd	lg	η	Θ	β	α	γ	C_{tot}	MST
RV_	01	31	33	426	1225	26	7	2	4	8	0,102	4,16	0,79	0,23	1,06	0,07	0,38	49,5	34,0
RV_	02	85	99	890	2628	42	20	1	15	14	0,028	6,63	0,42	0,24	1,16	0,09	0,40	142,0	111,0
RV_	03	57	73	670	2065	50	20	1	17	14	0,046	5,54	0,68	0,35	1,28	0,16	0,44	111,5	45,0
RV_	04	36	49	560	1570	28	10	1	14	9	0,078	4,14	0,57	0,28	1,36	0,21	0,48	76,5	49,0
RV_	05	46	48	932	2780	23	15	2	4	12	0,047	6,28	0,48	0,33	1,04	0,05	0,36	64,0	56,5
RV_	06	50	48	978	2674	17	22	2	0	11	0,039	5,13	0,35	0,44	0,96	0,00	0,33	73,5	56,0
RV_	07	43	50	870	2278	14	15	1	8	14	0,055	5,44	0,28	0,35	1,16	0,10	0,41	61,0	27,0
RV_	08	23	29	275	970	12	5	1	7	8	0,115	3,65	0,41	0,22	1,26	0,17	0,46	41,5	27,5
RV_	09	38	49	628	1319	22	10	1	12	11	0,07	4,793	0,45	0,26	1,29	0,17	0,45	73,5	45,0
RV_	10	53	62	797	2282	25	32	3	12	17	0,045	6,88	0,40	0,60	1,17	0,12	0,41	90,0	71,0
RV_	11	29	27	476	1374	20	12	2	0	14	0,067	5,97	0,74	0,41	0,93	0,00	0,33	37,0	37,0
RV_	12	10	11	152	335	5	2	1	2	5	0,244	2,49	0,45	0,20	1,10	0,13	0,46	14,5	11,5
RV_	13	49	54	362	1031	18	18	2	7	12	0,046	5,844	0,33	0,37	1,10	0,08	0,38	79,0	66,0
RV_	14	21	24	340	1024	25	12	1	4	8	0,114	3,767	1,04	0,57	1,14	0,11	0,42	34,0	25,0
RV_	15	55	63	209	629	12	6	1	9	8	0,068	3,386	0,19	0,11	1,15	0,09	0,40	34,0	25,0
RV_	16	55	63	882	2647	54	30	2	10	16	0,042	5,636	0,86	0,55	1,15	0,10	0,40	86,5	72,0
RV_	17	25	25	356	850	12	8	1	1	11	0,083	4,73	0,48	0,32	1,00	0,02	0,36	32,0	29,0
RV_	18	46	43	780	1305	20	18	1	0	20	0,042	7,85	0,47	0,39	0,93	0,00	0,33	54,0	52,5
RV_	19	27	29	273	771	28	10	1	3	7	0.097	3,40	0,97	0,37	1,07	0,06	0,39	76,5	49,0
RV_	20	50	62	503	1407	19	15	1	13	15	0,051	5,89	0,30	0,30	1,24	0,14	0,43	85,0	61,0

The table also includes the dimensionless parameter. There are low values for the rationalist architecture which developed after the Second World War. In fact, as you can see, the villas designed by Mies Van Der Rohe present better connectivity than any other.

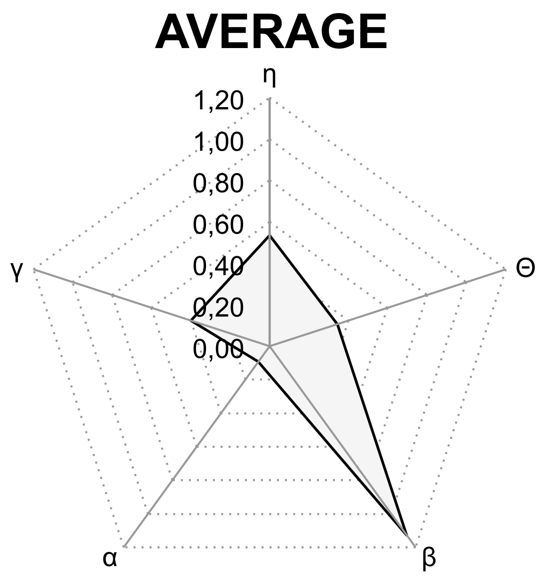


Figure 55 – Average of the value obtained for the “sampling” analysis

For further work, it would be possible to study buildings designed by the same architect: for instance, Alvar Aalto and his buildings could be explored in this direction to establish a “fingerprint” of his work.

The results achieved so far are partial and need a more in depth investigation that applies the method using a different typology that is more influenced by the circulation aspect.

5.2 Manchester City Library

The aim of this case study is to test the procedure on a real case study involving the renovation of a historical building. The redevelopment is part of a complex plan that involves the Town Hall Complex (THC) and the Manchester Central Library (MCL).

Essentially, *"Ryder's whole design concept rests on two fundamental architectural interventions. The first was to introduce a continuous, centralised vertical circulation core into the building for the first time. And the second was to reverse the 70/30 ratio of books on display. Both visions have an enormous impact on the building's wider renovation programme"*.[197]

The main design idea can be considered as an improvement regarding the connectivity between spaces. Our study begins with the analysis of the existing situation. The model was achieved from a mixed survey technique that has hybridized the use of laser scanners and direct surveys.

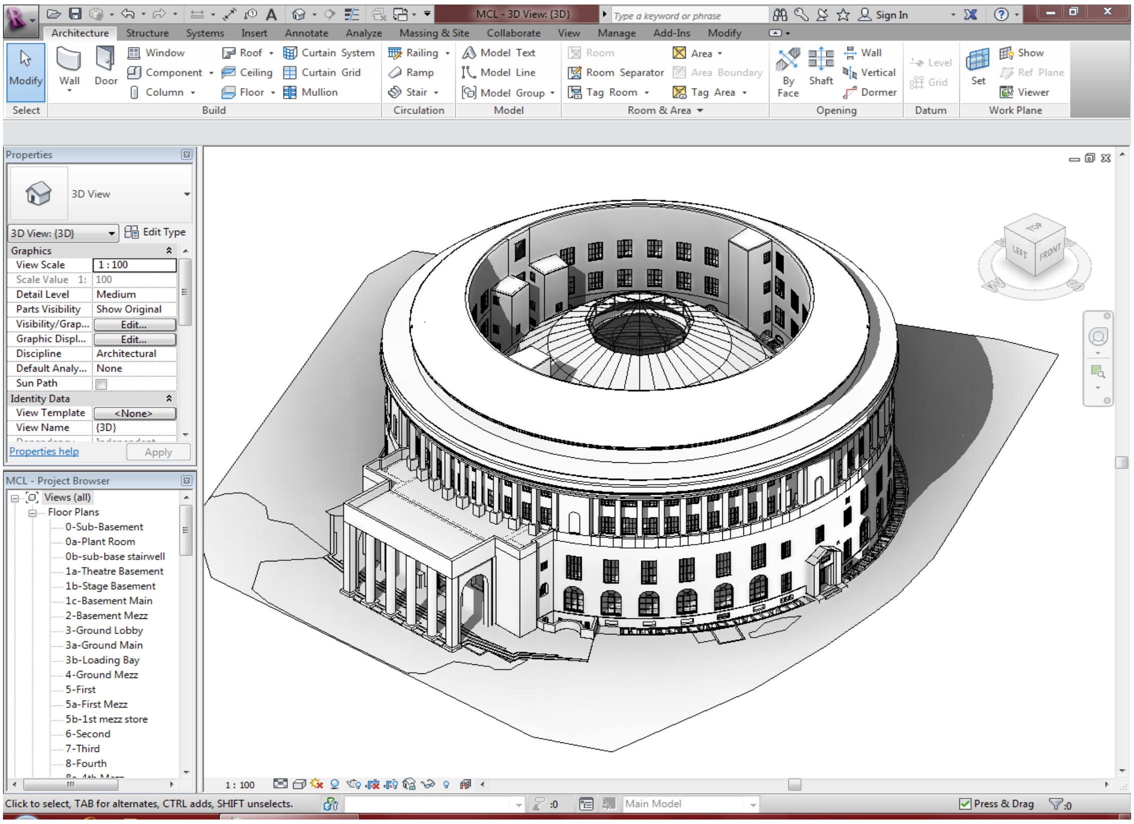


Figure 56 – "Inventory" BIM Model - MCL

[197] Ijeh, 2014.

Using the same colour convection as in the previous test, both horizontal and vertical connections are in red, services are in blue, and functional spaces are in yellow. An example of codification is shown in Figure 57.

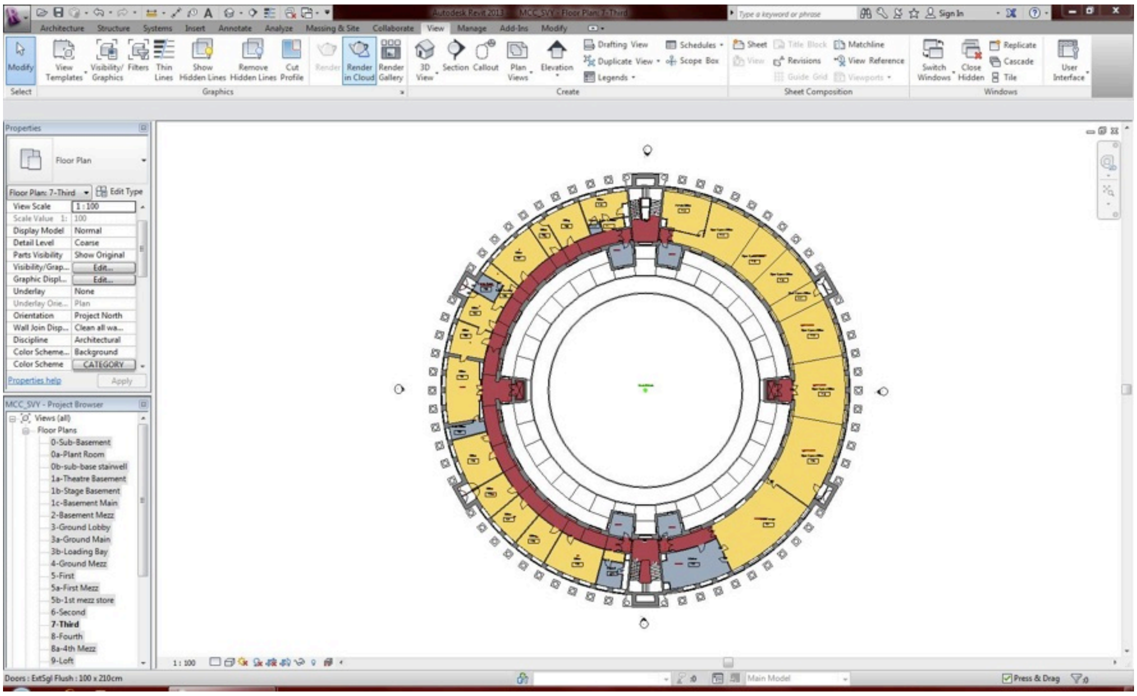


Figure 57 – Third Floor - MCL

This was exported into a list of spaces and edges (MCC_room.csv and MCC_edges.csv). The consistency check took place by verifying the theoretical graph drawn for each floor against the one obtained by manual technique.

Calculations of the parameters of the existing design solution are given in the following table.

Value:

v	e	A	V	L(g)	PE	p	u	d	g_d	I_g	η	Θ	β	α	γ	C_{tot}	MST
(space)	(edges)	(surface)	(volume)	(total leght)	(people)	(sub-cycle)	(cycle)	(diameter)	(density)	(av. leght)						(total cost)	(cost)
264	365	2783	8707	30	10	1	3	7	0.10	3,40	0,97	0,37	1,07	0,06	0,39	76,5	49

Obviously, the idea of this analysis was not to discredit the adopted project solution, but, on the contrary, to demonstrate that the method can be used to highlight the best position for a vertical core calculation. The solution which shows the best values in terms of connectivity may also the best in terms of architecture.

The general idea of the design is to verify the position of the vertical core that has to be placed in each quarter of the circular sector. In addition it hypostasizes the realization of a sky-bridge that connects two sides of the fourth floor by passing over the dome.

The figure below (Figure 58) shows the cases analysed. In particular, the position of the vertical core has been highlighted (solutions A to D) and what it is intended for the addition of sky-bridges (solution E).

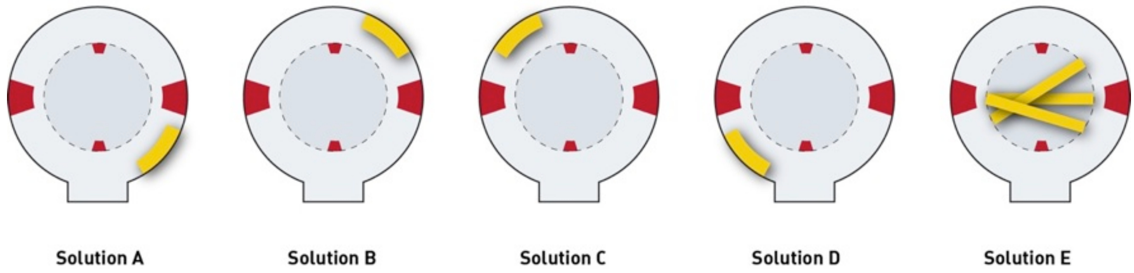


Figure 58 – Hypothesis of design solutions for MCL

The following table (Table 14) shows the numerical results obtained from the analysis.

Table 19 – Numerical result for MCL

	v (space)	e (edges)	A (surface)	V (volume)	L(g) (total leght)	PE (people)	p (sub-cycle)	u (cycle)	d (diameter)	gd (density)	lg (av. leght)	η	Θ	β	α	γ	C_{tot} (total cost)	MST (cost)
A	260	350	2783	8707	50	250	16	88	16	0,102	5,18	0,15	1,04	1,38	0,22	0,46	240,5	225,5
B	255	340	2783	8707	50	250	16	101	21	0,102	5,28	0,15	0,96	1,31	0,19	0,44	255,0	250,0
C	265	356	2783	8707	50	250	16	107	18	0,107	4,10	0,14	0,94	1,34	0,20	0,45	252,0	249,0
D	260	350	2783	8707	50	250	16	106	19	0,098	4,16	0,14	0,96	1,35	0,21	0,45	268,0	258,0
E	290	320	2783	8707	50	250	16	46	25	0,097	4,16	0,16	0,86	1,10	0,08	0,37	252,0	249,0

If we also observe the performance achieved we can affirm that in terms of connectivity solution A is the most efficient because it presents the highest values for the parameters β, α and γ, and a reduced value of η.

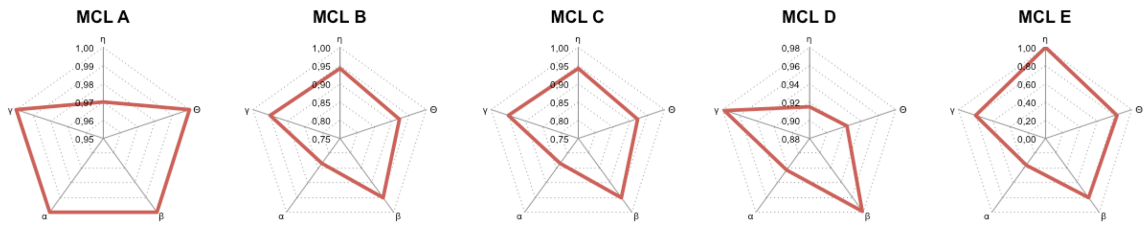
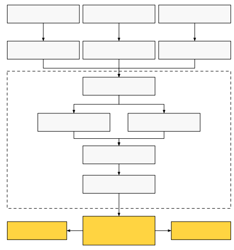


Figure 59 – Performance result for MCL

6 Conclusion



It has been demonstrated that the pre-design phase has complex responsibilities and plays a central role in the design stage. In fact, in this specific phase changes still have a low economical cost, rather than if they are remedied in later phases (especially the construction phase), which could have serious repercussions on the next stage. Minimizing the risk of failure of the project is essential. The method elaborated in this PhD thesis aims to contribute in this direction by giving references for evaluating design solutions in terms of connectivity.

The results achieved through this work have shown a correlation between “parameters” (described in detail in Appendix B) and distributive patterns. In particular, specific correlations for the dimensionless parameter have arisen, which have to be taken into account when evaluating connectivity (β and γ) or traffic (η and θ) within the building.

Furthermore, the results achieved with the “Sampling” experiment have revealed some ranges in which the parameters are specifically related to that typology, although it is necessary to proceed with the analysis of other typologies to compare this value with different types of buildings. In fact this is highlighted as one of the potential developments of the research. Possible developments could be conducted by gathering parameters from different types of building such as hospitals, airports and museums. Moreover, the analysis can proceed by considering the best cases of a specific typology that have already been built, and using Graph Theory to understand which are the critical points in the layout distribution and propose an improvement.

Other possible developments could be extended in the direction of the "automated assessment". Following the reasoning made until now, it is possible to analyse some specific distributive layout problems concerning topological relations between spaces, such as the determination of the best position for a vertical core. It will also be necessary to consider the topological graph rather than just the connectivity graph.

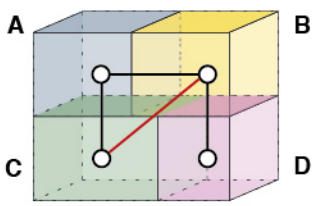


Figure 60 – Example of a possible problem for automatic detection of vertical core position

Figure 60 shows a typical problem of decision-making regarding the best way to connect spaces. If we think about connecting the spaces with a vertical core, we must consider the topological graph of the spaces shown in the figure. Space B directly touches space D (relation of “touch”) because they are overlapped vertically, but also partially touches space C and obviously A, horizontally.

When determining the possibility of installing an elevator or a stairwell we can associate a weight with each link of the topological graph that may represent several aspects such as the distances between spaces, the intensity of work necessary to demolish some partitions, the percentage of overlapping between partitions (both horizontal and vertical), the time necessary to reach the space and so on. Obviously all these conjectures need an in-depth analysis in order to validate this last hypothesis.

It is necessary, at the end of this work, to argue that creativity and intuition cannot be substituted in the process of design by an automated tool. The “machine”, as in all of its aspects, can be used to assist the designer during this process, especially in those context in which the circulation and aspects are dominant. Some techniques such as the procedures described here can be useful when evaluating the process of pre-design.

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Appendix A: Definitions [198]

Intervention on an existing building

Means a group of possible activities that have to be carried out to modify the status of the building.

Renewal

This word is related to the concept of the general approach to urban design either as the creation of new urban "portions" or as modernisation of the old parts. Modernisation means repairing the old parts that are falling into ruin, it means updating the quality standards of the living conditions, it means introducing social facilities. Regarding the urban scale it concerns the substitution of the existing urban texture with a different one by inserting a system group of building works. It may even enhance completely the site, the blocks and road network.[199]

Redevelopment

This is a big "container concept" that is synthetically used to consider the design-approach towards existing building heritage, that has the aim of completing all the technical steps necessary to maintain and reuse buildings and areas that are in bad condition (statically, functionally aesthetically speaking).[200]

Restoration

This is a process aimed at conserving an historical building to increase its durability across its whole original character. Every work will be in the sense of preserving the original structure, the original architectural aspect and style, the original materials and (when possible) the building original technique. In particular for buildings for which "restoration" is the only kind of work allowed, it is not usually possible to change the original function."[201]

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[198] The following definition are referred to: Capone, P.; Ronconi F. (2000). "Pianificazione e gestione tecnico-amministrativa del processo edilizio nel recupero funzionale ed ecologico di aree destinate alla residenza sociale – Verso una cultura europea per una strategia comune. Ed. Medicea. Firenze.

[199] Capone and Ronconi, 2000, p.16.

[200] Idem.

[201] Idem.

Moreover, restoration projects are not only about the historical, although they are commonly understood as such, but they also apply to buildings or groups of buildings that have a history. The terminology to be used in restoration projects is standardized by the European protocol "UNI 10914-1:2001. Qualification and control of the construction project of a new building interventions and interventions built – Terminology."

Space in architecture

Space is one of the basic concepts by which we refer to the material world. For many reasons it is not easy to define the term space within a theory of architecture. One of the clearest definitions of space is that given by Zevi:

Paint acts in two dimensions, although it may suggest three or four. Sculpture acts in three dimensions, but man is left outside, looking separately from the external three dimensions. Architecture is rather like a large sculpture carved inside which the man penetrates and walks through. (...) Architecture is not derived from a sum of widths, lengths and heights of the building elements that enclose the space, but just the empty space enclosed, interior space in which men walk and live (...). The internal space, that (...) cannot be fully represented in any form, that cannot be learned and lived if not for direct experience (...).[202]

The spatial experience within architecture is extended into the city, into the streets, squares, parks, stadiums and gardens. Wherever man's work has limited the “empty”, he has created enclosed spaces. Now, since each building has volume, each box wall is a limit, a break in the continuity of space, it is clear that any building works to create two spaces: the interior, fully defined by the work of architecture, and the exterior, or urban, enclosing this work and its neighbours. It is evident that all of those elements external to the architecture itself – bridges, obelisks, fountains, triumphal arches, groups of trees, etc. – and particularly the facades of buildings, all come into play in the creation of urban space.

In the end it is natural to consider space, emptiness, as the protagonist of architecture because architecture is not only art, it is not only the image of a historical life or life lived by us and by others; it is also and above all, the environment, the site where our life takes place.

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[202] Zevi, 1997, p. 21–33.

This everyday understanding of space may be self-evident and unproblematic. However, as soon as we are asked for a formal definition, for example in the context of building classification or product modelling, the concept of space is subject to controversy and misunderstanding.

For some, space is the emptiness between things, or the emptiness in which things are embedded, for instance immaterial things. For others, space has no separate existence but is a property of the material world. Nevertheless, according to both views, space can be experienced.

Space in BIM

From the point of view of computer technology, "space" has come to be an important concept both for building construction and the process of facility management.

OmniClass define a space as *"a segment of the built environment that is marked off from other spaces and elements in some way. It is usually a component part of a larger, more significant construction entity. A space can be delineated by either physical or abstract boundaries. These boundaries determine the form of the space, which can be three-dimensional such as a room, or a two-dimensional surface such as a walkway. The form of the space can create a medium for action or movement, which is related to the function of the space. Many spaces are also largely unoccupied, but serve a function within the facility"*.[203]

If we refer to the standard definition of those elements connected with the IFC, the International Alliance for Interoperability (IAI) defines space as follows: *"(Ifcspace) represents an area or volume bounded actually or theoretically. Spaces are areas or volumes that provide for certain functions within a building. A space is (if specified) associated to a building storey (or in case of exterior spaces to a site). A space may span over several connected spaces. Therefore a space group provides for a collection of spaces included in a storey. A space can also be decomposed in parts, where each part defines a partial space".*[204]

Bormann presents a method of topological relationships for building elements.[205] This method can be generalized and applied to some possible spatial operations. The general treatment considers topological relationships that are **disjointed**, **equal**, **contained**, **overlapping**, **within** and **touching** (Figure 61).

[203] OmniClass, Table 14.

[204] BuildingSMART, 2014.

[205] Borrmann & Rank, 2009.

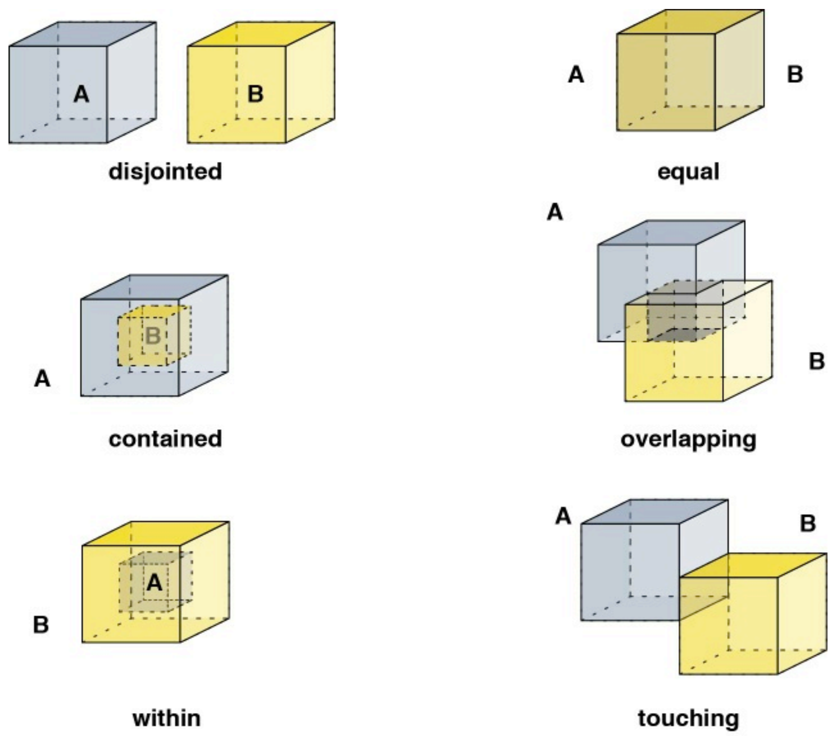


Figure 61 – Topological relations

In architecture, and especially with existing buildings, the permitted topological operations are usually reduced to “**touching**”, because usually a historical building has a chain of consecutive spaces that are connected to each other, and “**within**”, because it is possible to divide the original space. Other operations are possible but rare. For instance, “overlapping” can be used to generate a particular space, but this will massively involve the structural elements. The “contained” operator can also be associated with the creation of an additional structure that covers and wraps the original space, but this case will also involve a large effort to build a complex structure.

These types of separation between spaces provide important criteria regarding subdividing space and considering different activities. The operator “within” is usually related to a spatial group or space where this last includes, within a macro boundary, the operator that is visibly “touching” between spaces, usually represented by a physical or virtual separation.

Distributive scheme

Before describing in detail the proposed methodology for an automated assessment of a building re-design, it is necessary to clarify some concepts and terms.

The process of sketching and realizing a schematic design refers to the general concept of representing, using the minimum of signs, a distributive scheme and relationships between entities. A “**distributive scheme**” is the sum of these signs: it is an image that is neither realistic nor abstract because it is the graphical summary of a concept that derives from the experience. This is very similar, in many ways, to the transcendental activity investigated by Kant, which justifies its adopted name of “scheme”.[206]

As there are different degrees or types of design, each capable of giving different formal information, so the terms “**functional scheme**” and “**distributive scheme**” are different. With “functional” we refer indirectly to a space, but under the term "distributive" it is possible to consider different kinds of information: for instance, orientation of the sun, lighting and exposition; or, if we change scale and consider a room, determining the behaviour through fixed or removable furniture in order to determine the minimum functions gives rise to different types of patterns.

Although a more complete discussion is needed in order to define all the various aspects of design, in the context of this work we focus mainly on the communication between spaces, which we briefly call “**circulation**”.

[206] Koenig, 1962.

Appendix B: Parameters

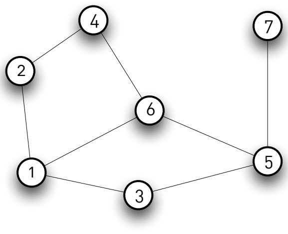
When analysing graph efficiency several measures and indices can be used to express the relationship between values and graph structures. In addition, “*indices are more complex methods to represent the structural properties of a graph since they involve the comparison of a measure over another. Some indices take into account spatial features (distance, surface) as well as the level of activity (traffic between spaces), while others solely rest on the topological dimension of the network*”.[207]

Indexes and parameters are related to two different scales: the graph scale and the node scale. Our approach will take into account only parameters in relation to the graph scale.

All the material reported in this chapter was elaborated from the work of Ducret and Rodrigue, listed in the Bibliography.

Diameter (d)

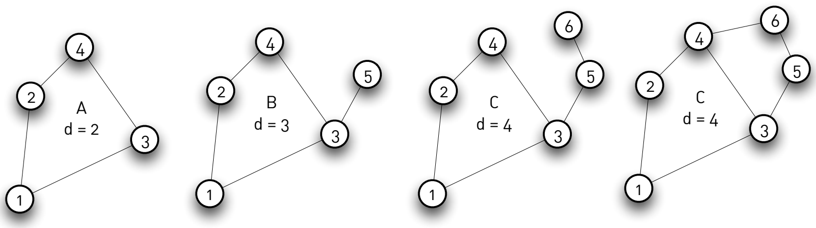
Diameter is the shortest path length between the most remote nodes in a graph. It is expressed by the letter “d”.



Diameter (d) = 4

$$A = \begin{array}{c} \\ 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ 6 \\ 7 \end{array} \begin{array}{c} \begin{array}{ccccccc} 1 & 2 & 3 & 4 & 5 & 6 & 7 \end{array} \\ \begin{bmatrix} 0 & 1 & 1 & 2 & 2 & 1 & 3 \\ 1 & 0 & 2 & 1 & 3 & 2 & 4 \\ 1 & 2 & 0 & 3 & 1 & 2 & 2 \\ 2 & 1 & 3 & 0 & 2 & 1 & 3 \\ 2 & 3 & 1 & 2 & 0 & 1 & 1 \\ 1 & 2 & 2 & 1 & 1 & 0 & 2 \\ 3 & 4 & 2 & 3 & 1 & 2 & 0 \end{bmatrix} \end{array}$$

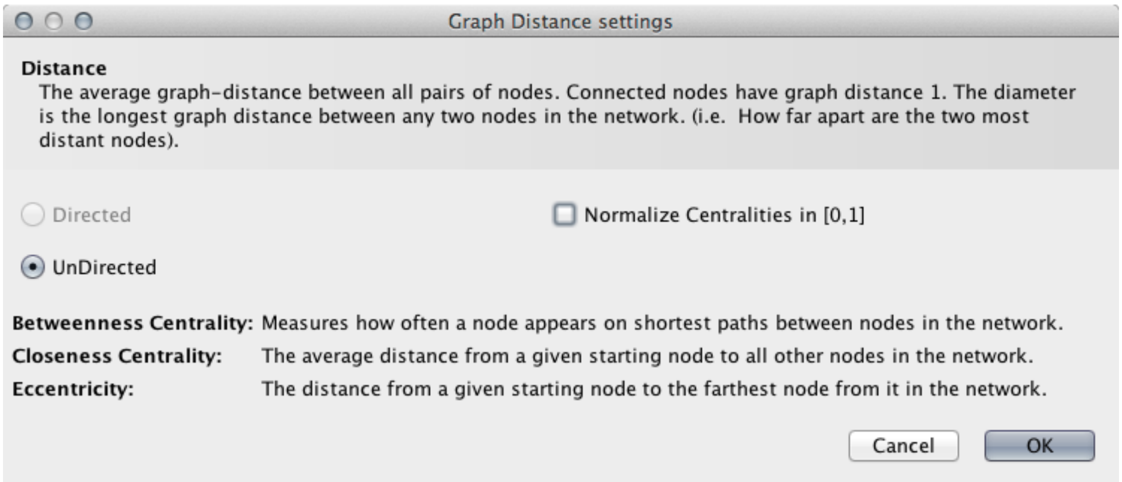
The highest value for the topological distance of this matrix is the diameter of the graph (d=4). In the case of a non-oriented graph, the matrix is transposable. The diameter enables us to measure the development of a graph or network over time. In the context of design it may be useful for evaluating the flexibility of a solution.



[207] Ducruet & Rodrigue, 2013.

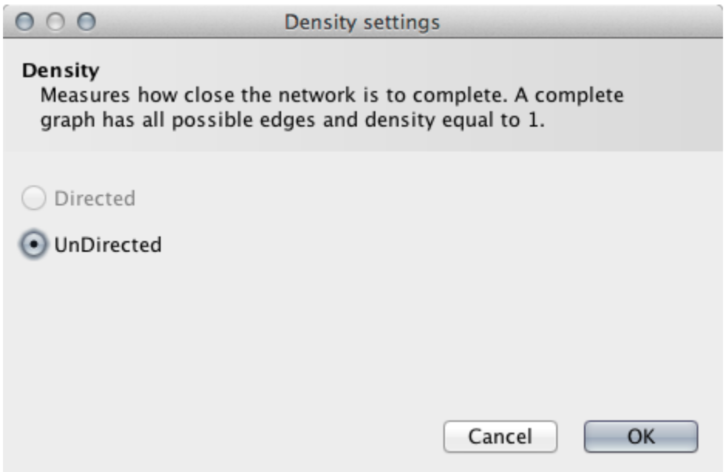
The larger the diameter, the less connected a graph tends to be. Graphs of equal size but with a higher connectivity have lower diameter values.

The diameter can be calculated automatically in Gelphi.



Density (gd)

The density of a graph represents how close the graph is to a complete graph with the same number of nodes. The higher the density the more it is developed. Density can also be calculated automatically in Gelphi.



Average shortest path length (lg)

Measurements related to the number of nodes and links (such as the α, β, and γ indices) are limited in revealing the structural differences between two graphs of equal size. More robust measurements have thus been proposed by physics, which take into account the internal complexity of the graph.

One measure of efficiency is the average number of stops needed to reach two remote nodes in the graph. The lower the result, the more efficient the network is at providing ease of circulation. In comparison, the diameter is the maximum length of all possible shortest paths.

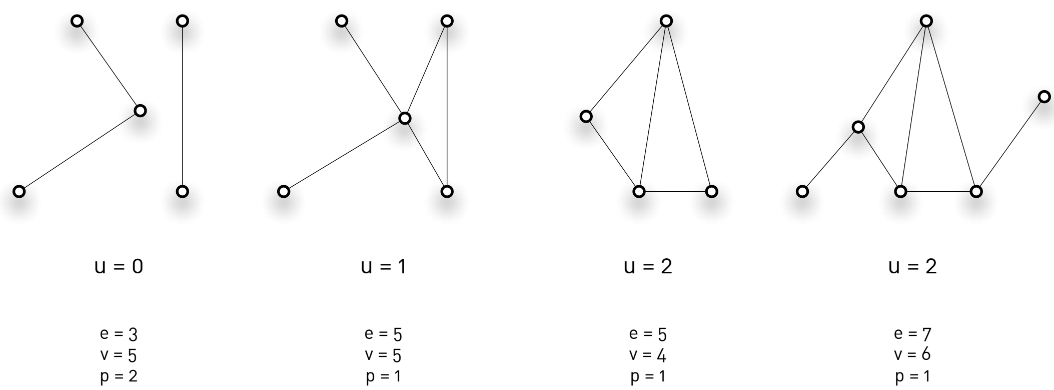
$$l_G = \frac{1}{n(n-1)} \sum_{i \neq j} d(v_i, v_j)$$

Where n is the number of vertices of the graph G and $d(v_i, v_j)$ is the shortest distance between two generic vertices.

Number of independent cycles (u)

The number (u) is calculated using the number of nodes (v), links (e) and sub-graphs (p). Trees and simple networks have a value of 0 since they have no cycles. The more complex a network is, the higher its u value. This means it can be used as an indicator of the level of development and complexity of a transport system.

$$u = e - v + p$$



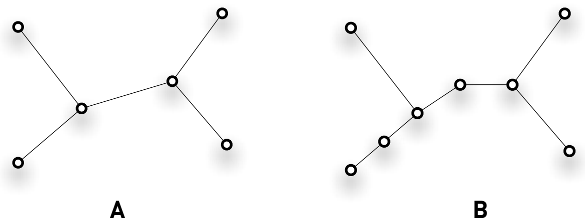
In architecture the significance of the cycle is that it represents different accessible paths to a given node. For instance, if we refer to the work of Mies Van Der Rohe (see Chapter 5), we can see a more consistent number of cycles in his later work than at the start of his career. This development is aligned with his view that architecture should create a space of free movement without barriers.

η index (eta index)

This index represents the average length per connection. Adding new nodes will decrease the value of eta as the average length per link decreases.

$$\eta = \frac{L(G)}{e}$$

	L (G)	e	η
A	80 m	5	16
B	80 m	7	11.4



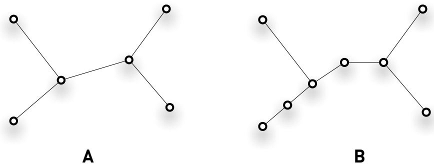
Eta provides important information about the fragmentation of space: adding nodes can mean separating the space into more sub-spaces.

Θ index (theta index)

This index measures the function of a node; that is, the average amount of traffic per intersection. The higher θ is, the greater the load of the graph. This measurement can also be applied to the number of links (edges). For instance, the load can be associated with the approximate number of persons within the building.

$$\theta = \frac{Q(G)}{v}$$

	Q (person)	**v**	**θ**
A	35	6	5.833
B	35	8	4.375



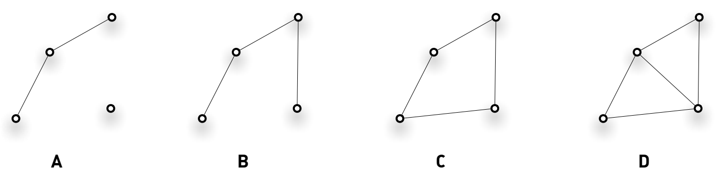
β index (beta index)

This measures the level of connectivity in a graph and is expressed by the relationship between the number of links (e) over the number of nodes (v). Trees and simple networks have a beta value of less than one. A connected network with one cycle has a value of 1. More complex networks have a value greater than 1 (Ducruet & Rodrigue, 2013).

In a graph with fixed nodes, the higher the number of links, the higher the number of possible paths within the graph. Complex graphs have a high value of β.

$$\beta = \frac{e}{v}$$

	e	v	β
A	2	4	0.5
B	3	4	0.75
C	4	4	1.0
D	5	4	1.25



The four graphs above represent an increasing connectivity. Graphs A and B are not fully connected and their β value is less than 1. Graph C is connected and has a β value of 1. Graph D is over-connected and has a β value of 1.25.

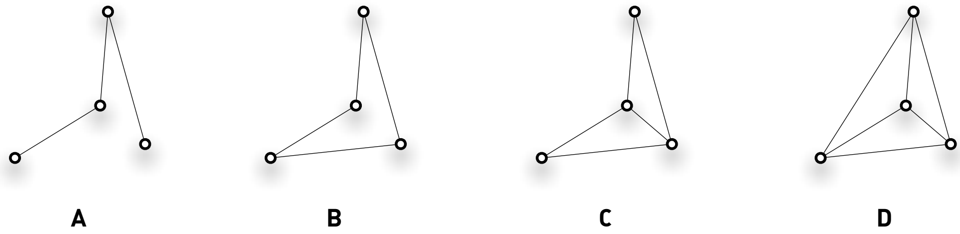
α index (alpha index)

This index measures connectivity by evaluating the number of cycles in a graph in relation to the maximum number of cycles. The higher the α index the more connected the graph is. Trees and simple networks will have a value of 0. A value of 1 indicates a completely connected network.

The alpha index measures the level of connectivity independently of the number of nodes. It is very rare that a network will have an α value of 1, because this would imply serious redundancies. In the literature on planar networks this index is also called the meshedness coefficient.

$$\alpha = \frac{u}{2v-5}$$

	u	2v-5	α
A	0	3	0.0
B	1	3	0.33
C	2	3	0.66
D	3	3	1.0



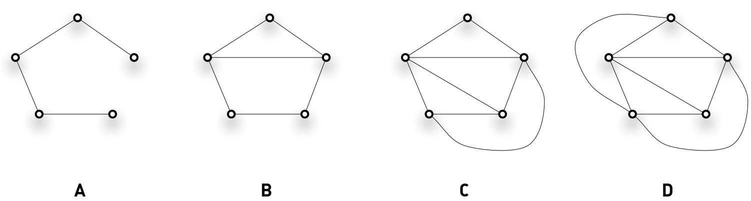
The above graphs have an increasing level of connectivity. While graph A has no cycles, graph D has the maximum possible number of cycles for a planar graph.

γ index (gamma index)

This is a measure of connectivity that considers the relationship between the number of observed links and the number of possible links. The value of gamma is between 0 and 1, where a value of 1 indicates a completely connected network, something that is extremely unlikely in reality. The gamma index is an efficient way of measuring the progress of a network over time.

$$\gamma = \frac{e}{3(v-2)}$$

	e	3(v-2)	Φ
A	4	9	0.44
B	6	9	0.66
C	8	9	0.88
D	9	9	1.0



The above graphs show an increasing level of connectivity, with graph D having the maximum number of links (9) and a gamma index of 1.0.

Cost (C)

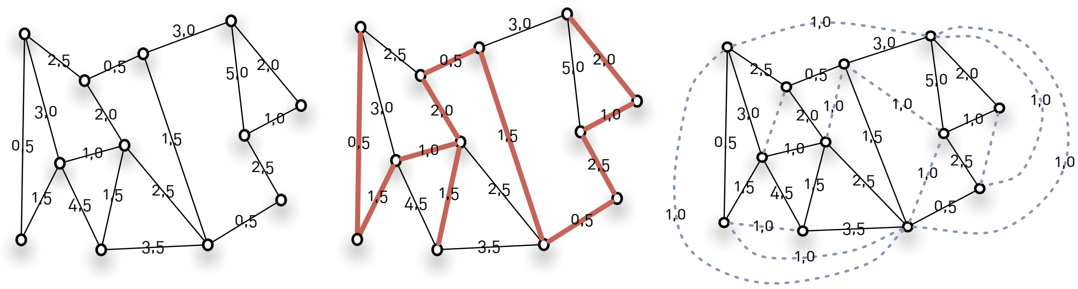
Cost is the total length measured by the weight of the edges: $\mathbf{a_{ij}}$ is the presence (1) or absence (0) of a link between i and j, and $\mathbf{l_{ij}}$ is the weight of the links. Cost can also be calculated on the basis of two other dimensions of the network: the **minimum spanning tree** (MST) and the **complete graph** (CG).[208]

The MST represents the shortest and/or lowest cost sub-tree of the graph. It can be obtained by applying, among other shortest path algorithms, the **Kruskal algorithm**, which finds the lowest cost route that connects all nodes in the network.

The CG refers to the same number of nodes as in the original network but with all possible links added to achieve a complete graph. This type of graph is impossible in architecture, but it is used as a reference for the highest level of connectivity. More efficient graphs have relative costs that are closer to 1, while less efficient networks are closer to 0.

$$Cost = \sum_{i,j} a_{ij}\ l_{ij} \qquad Cost_{rel} = \frac{Cost - Cost^{MST}}{Cost^{CG} - Cost^{MST}}$$

	Cost (weight)	Cost (links)
(1)	36.0	18
(2)	14.5	11
$Cost_{rel}$	0.642	0.389



(1) Original Graph Weight link **(2) Minimum Spanning Tree (MST)** **(3) Complete graph (CG)**

The Kruskal algorithm extracts the optimal cost route from the original network. This is defined as a single line that joins all the nodes at a minimum cost (Minimum Spanning Tree). Values of 1 at each newly created link are assigned in the abstract due to the absence of a unit measurement (which may be transit time of transit in meters/second, for instance).

In the form given above, the graph reported in the image underneath is more efficient in terms of weight ($Cost_{Rel}$ = 0.642) than in terms of links ($Cost_{Rel}$ = 0.389).

[208] This last wasn't taken into account during this thesis.

In an architectural layout it makes sense to conduct the analysis floor by floor and consider the graph on the plane of each given level. More difficulties arise if we try to flatten the entire graph. Through this procedure we may lose important information that is created by the hierarchical order of several tiers.

Summary prospectus of how parameters are calculated

Table 20 shows the list of the parameters previewed and the software used to achieve them. Some parameters are calculated automatically with simple formulas in Excel; others through the use of specific software such as Gelphi and MatLAB.

Table 20 – Summary prospectus

Parameter or index	**Tool**
Number of vertices, edges and subs	Gelphi (from .csv file imported and read from context menu)
Dimensional data (area and volume)	Revit (from room schedule)
Diameter (d)	Gelphi
Density (g_d)	Gelphi
Average shortest path length (l_g)	Gelphi
η index	Excel
Θ index	Excel
β index	Excel
α index	Excel
γ index	Excel
Cost $_{tot}$	MatLAB (routine attached in the following paragraph)
Cost $_{MST}$	MatLAB
Cost $_{CG}$	MatLAB

```matlab
% Calculate of Total Cost and MST Cost of the graph
% 1 - Import edge.csv in matlab:

% ‘edges.csv’ is the input file
% the function “csvimport” can be downloaded from:
% http://www.mathworks.com/matlabcentral/fileexchange/23573-csvimport
edges = csvimport ('edges.csv');

% 2 - Resizing .csv file:
% (Deleting first row and other not necessary columns)
edges (1,:)= [];
edges (:,3:5)=[];
rooms= rooms (:,2);

% 3 - Convert cell array in numerical array:
edges = cell2mat(edges);

% 4 - Extract vectors (lsit1, list2, W weight of connections):
list1 = edges(:,1);
list2 = edges(:,2);
W = edges(:,3);

% 5 - Assembly of the sparse matrix:
DG = sparse (list1, list2, W);

% 6 – Control point, if DG is not square
% Convert into full matrix
DGfull=full(DG);

% 7 – dimension of the matrix
[m,n] = size(DGfull);

% cycle if to control if m and n are equal


if m~=n
  if (m>n) max=m;
    else max=n;
  end
```

```
    A=zeros (max,max);
    %B=zeros (max,max);

    A(1:m,1:n)=DGfull;
    DG=sparse (A);

end

    % 8 - Convert sparse matrix into symmetrical full matrix:
    UG = tril (DG + DG');

    % 9 – possibility to visualize the result for cheeking
    %view(biograph(UG,[],'ShowArrows','off','ShowWeights','on'))

    % 10 – Kruskal algorithm implemented in MatLAB
    [ST,pred] = graphminspantree(UG);
    %view(biograph(ST,[],'ShowArrows','off','ShowWeights','on'))

    % 11 - Calculation of total cost and MST cost
    Cost_tot= sum(W)
    STfull=full(ST);
    Cost_mst=sum(STfull(:))
```

Appendix C: Code in C# for Revit

D1 - The plug-in for Autodesk Revit

This appendix presents the code for the Autodesk Revit plug-in. It is necessary to acknowledge and thank Dr. Simone Saraceni (software engineer) who helped with writing and debugging the code. Without his support it would not have been possible to achieve these results.

The plug-in is based on the constitution of three codes, subdivided into:

1. Class.cs – the core of the plug-in;
2. RoomLink.cs – code for understanding relations to the individuation;
3. OpeningInfo.cs – code for understanding relations between spaces;

The code is given in the following text.

D2 - Class.cs

```
using Autodesk.Revit.Attributes;
using Autodesk.Revit.DB;
using Autodesk.Revit.DB.Architecture;
using Autodesk.Revit.UI;
using QuickGraph;
using System;
using System.Collections.Generic;
using System.IO;
using System.Linq;
using System.Text;
using System.Threading.Tasks;
using System.Windows.Forms;
using Util;

[TransactionAttribute(TransactionMode.Manual)]
[RegenerationAttribute(RegenerationOption.Manual)]

//
// Summary:
//   Main class - Entry point for Revit Plugin
//
public class Plugin : IExternalCommand
{
  public Result Execute(
    ExternalCommandData commandData,
    ref string message,
    ElementSet elements)
  {
    try
    {
      //Get application and document objects
      UIApplication uiApp = commandData.Application;
      Document doc = uiApp.ActiveUIDocument.Document;

      //Create a filter to list levels on active document
      ElementCategoryFilter                levelFilter                 =                 new
ElementCategoryFilter(BuiltInCategory.OST_Levels);
```

```
      FilteredElementCollector collLevel = new FilteredElementCollector(doc);
      ICollection<Element> levels = collLevel.WherePasses(levelFilter).ToElements();

      //Create and display a dialog to save a file with the list of rooms
      SaveFileDialog dialog = new SaveFileDialog();
      dialog.Title = "Save ROOMS";
      dialog.Filter = "CSV files (.csv) | *.csv";
      String name = "rooms.csv";
      dialog.FileName = name;
      if (dialog.ShowDialog() == DialogResult.OK) name = dialog.FileName;

      //Create a list of openings with hosting wall
      Dictionary<ElementId, OpeningInfo> openings = getOpeningsInfo(doc);
      List<ElementId> specRooms = new List<ElementId>();
      Dictionary<ElementId, int> listRoomsID = new Dictionary<ElementId, int>();

      //prepare a stream to write rooms info into file
      StreamWriter writer = new StreamWriter(name);
      int count = 2;
      writer.WriteLine("roomId;id;label;level;area;volume");
      writer.WriteLine("outside;1;outside;;;");
      //lists rooms for each level
      foreach (Element l in levels)
      {
        if (l.GetType() == typeof(Level))
        {
          try
          {
            PlanTopology pt = doc.get_PlanTopology((Level)l);
            foreach (Room r in pt.Rooms)
            {
              //add current room to file
              writer.WriteLine(r.Id.ToString() + ";"+count+";" + r.Name + ";" + l.Name +
";" + r.Area + ";" + r.Volume);
              listRoomsID.Add(r.Id, count);
              //verify name for special rooms type and add to a list
              if      (r.Name.StartsWith("ST")      ||      r.Name.StartsWith("EL")      ||
r.Name.StartsWith("RP"))
              {
                specRooms.Add(r.Id);
              }
              count++;
              //verify if the room is connected to another by an opening
              isWallinRoom(r, openings);
            }
          }
          catch (Exception eee) { }
        }
      }
      writer.Close();
      writer.Dispose();

      //Create a filter to list doors on active document
      ElementClassFilter              familyInstanceFilter              =              new
ElementClassFilter(typeof(FamilyInstance));
      ElementCategoryFilter              doorsCategFilter              =              new
ElementCategoryFilter(BuiltInCategory.OST_Doors);
      LogicalAndFilter  doorInstanceFilter  =  new  LogicalAndFilter(familyInstanceFilter,
doorsCategFilter);

      FamilyInstance myDoor = null;
      FilteredElementCollector collector = new FilteredElementCollector(doc);
      ICollection<Element>                              doors                              =
collector.WherePasses(doorInstanceFilter).ToElements();
      //obtain all room links
      List<RoomLink> separators = getRoomSeparators(doc);

      //create and display a dialog to save a file with connections between rooms
      dialog = new SaveFileDialog();
      dialog.Title = "Save connections";
      dialog.Filter = "CSV files (.csv) | *.csv";
      name = "edges.csv";
      dialog.FileName = name;
      if (dialog.ShowDialog() == DialogResult.OK) name = dialog.FileName;

      writer = new StreamWriter(name);
      int srcID, targID;
```

```
      ElementId appElID;
      writer.WriteLine("Source;Target;Type;Id;Label;Weight");
      foreach (Element d in doors)
      {
        myDoor = null;
        if (d is FamilyInstance)
        {
          myDoor = d as FamilyInstance;
        }
        else if (d is IndependentTag)
        {
          IndependentTag tag = d as IndependentTag;
          myDoor = doc.get_Element(tag.TaggedLocalElementId) as FamilyInstance;
        }
        if (myDoor != null)
        {
          srcID=1;
          if (myDoor.FromRoom!=null){
            appElID=myDoor.FromRoom.Id;
            if (listRoomsID.ContainsKey(appElID))
              srcID=listRoomsID[appElID];
          }
          targID = 1;
          if (myDoor.ToRoom != null)
          {
            appElID = myDoor.ToRoom.Id;
            if (listRoomsID.ContainsKey(appElID))
              targID = listRoomsID[appElID];
          }
          //add doors connection between rooms with weight=1.5
          writer.WriteLine( srcID+ ";" + targID + ";Undirected;" + myDoor.Id.ToString() +
";" + ((myDoor.ToRoom == null || myDoor.FromRoom == null) ? "Extern" : "") + ";1.5");
        }
      }

      //add openings info to file
      foreach (OpeningInfo o in openings.Values)
      {
        if (o.isComplete())
          writer.WriteLine(o.writeFile(listRoomsID));
        //verify if there is any room link with the same rooms connected by the opening,
and mark as already added
        foreach (RoomLink rl in separators)
        {
          if (rl.isEqual(o)) break;
        }
      }
      //add to file room links for rooms NOT connected by an opening
      foreach (RoomLink rl in separators)
      {
        if (rl.isNew())
          writer.WriteLine(rl.writeFile(listRoomsID));
      }
      //control special rooms (elevators, stairs) and add to file
      linkSpecialRooms(specRooms, doc, writer,listRoomsID);

      writer.Close();
      writer.Dispose();

      //save a file for windows
      dialog = new SaveFileDialog();
      dialog.Title = "Save Windows";
      dialog.Filter = "CSV files (.csv) | *.csv";
      name = "windows.csv";
      dialog.FileName = name;
      if (dialog.ShowDialog() == DialogResult.OK) name = dialog.FileName;

      writer = new StreamWriter(name);

      writer.WriteLine("Room;Id;Label");
      getWindows(doc,writer);
      writer.Close();
      writer.Dispose();

      TaskDialog.Show("Revit", "Files created");
      return Result.Succeeded;
    }
```

```
    catch (Exception e)
    {
      message = e.Message;
      return Result.Failed;
    }
  }

  // Summary:
  //   create a list of windows and add to file
  private List<Element> getWindows(Document doc,StreamWriter writer)
  {
    ElementClassFilter familyInstanceFilter = new
ElementClassFilter(typeof(FamilyInstance));
    ElementCategoryFilter winCategFilter = new
ElementCategoryFilter(BuiltInCategory.OST_Windows);
    LogicalAndFilter winInstanceFilter = new LogicalAndFilter(familyInstanceFilter,
winCategFilter);

    FilteredElementCollector collector = new FilteredElementCollector(doc);
    ICollection<Element> windows = collector.WherePasses(winInstanceFilter).ToElements();
    FamilyInstance myWin;
    foreach (Element d in windows)
    {
      myWin = null;
      if (d is FamilyInstance)
      {
        myWin = d as FamilyInstance;
        //   GetSubAndSuperComponents(myDoor);
      }
      else if (d is IndependentTag)
      {
        IndependentTag tag = d as IndependentTag;
        myWin = doc.get_Element(tag.TaggedLocalElementId) as FamilyInstance;
      }
      if (myWin != null && myWin.Room!=null)
      {
        writer.WriteLine(myWin.Room.Id.ToString() + ";" + myWin.Id.ToString() + ";" +
myWin.Name);
      }
    }

    return null;
  }
  // Summary:
  //   verify if there are some lines for area separations.
  //
  // Returns:
  //   a list of room links
  private List<RoomLink> getRoomSeparators(Document doc)
  {
    ElementCategoryFilter sepFilter = new
ElementCategoryFilter(BuiltInCategory.OST_AreaSeparationLines);
    FilteredElementCollector collSep = new FilteredElementCollector(doc);
    IList<Element> separators = collSep.WherePasses(sepFilter).ToElements();
    List<RoomLink> links = new List<RoomLink>();
    foreach (Element separ in separators)
    {
      try
      {
        BoundingBoxXYZ box = separ.get_BoundingBox(null);
        IList<Room> rooms = new List<Room>();
        Room lastR = null, testR = null;
        XYZ testP;
        double diffX = box.Max.X - box.Min.X;
        double diffY = box.Max.Y - box.Min.Y;
        bool yetAdded = false;
        if (diffX < 0) diffX = Math.Abs(diffX);
        if (diffY < 0) diffY = Math.Abs(diffY);
        testR = doc.GetRoomAtPoint(box.Max);
        if (testR != null) rooms.Add(testR);
        for (double i = -0.3; i <= (diffX + 0.3); i += 0.5)
        {
          for (double j = -0.3; j <= (diffY + 0.3); j += 0.5)
          {
            testP = new XYZ(box.Min.X + i, box.Min.Y + j, box.Min.Z);
            testR = doc.GetRoomAtPoint(testP);
            if (testR != null)
```

```
            {
              yetAdded = false;
              foreach (Room rt in rooms)
              {
                if (rt.Id.IntegerValue == testR.Id.IntegerValue) yetAdded = true;
              }
              if (!yetAdded)
              {
                rooms.Add(testR);
              }
            }
          }
        }
        int tot = rooms.Count;
        if (tot == 2)
        {
          links.Add(new RoomLink(separ, rooms[0], rooms[1]));
        }
        else
        {
          for (int i = 0; i < tot; i++)
          {
            testR = rooms[i];
            for (int j = i + 1; j < tot; j++)
            {
              lastR = rooms[j];
              if (lastR.Id.IntegerValue != testR.Id.IntegerValue)
              {
                links.Add(new RoomLink(separ, testR, lastR));
                j = tot;
              }
            }
          }
        }
      }
      catch (Exception ee){ }
    }
    return links;
  }
  // Summary:
  //   scan all special rooms and add to file, with the right weight
  private  void  linkSpecialRooms(List<ElementId>  specRooms,  Document  doc,  StreamWriter
writer,Dictionary<ElementId,int> listRoomsID)
  {
    Room specR, spec2;
    String lastName, newName;
    int lastObj, newObj;
    int lastFloor, newFloor;
    int pos;
    int src, targ;
    double w = 1;
    //scan all special rooms
    for (int i = 0; i < specRooms.Count; i++)
    {
      //identify type of room, number and level
      specR = (Room)doc.get_Element(specRooms[i]);
      lastName = specR.Name.Substring(0, 2);
      pos = specR.Name.LastIndexOf("-");
      lastObj = Int16.Parse(specR.Name.Substring(2, pos - 2));
      lastFloor = Int16.Parse(specR.Name.Substring(pos + 1, specR.Name.LastIndexOf(" ") -
pos));
      //search on all remaining rooms the same type of rooms, with the same number, and the
previous (or next) level number
      for (int j = i + 1; j < specRooms.Count; j++)
      {
        spec2 = (Room)doc.get_Element(specRooms[j]);
        newName = spec2.Name.Substring(0, 2);
        if (newName.Equals(lastName))
        {
          pos = spec2.Name.LastIndexOf("-");
          newObj = Int16.Parse(spec2.Name.Substring(2, pos - 2));
          if (newObj == lastObj)
          {
            newFloor = Int16.Parse(spec2.Name.Substring(pos + 1, specR.Name.LastIndexOf("
") - pos));
            if ((newFloor == (lastFloor + 1)) || (newFloor == (lastFloor - 1)))
            {
```

```
                if (newName.ToUpper().Equals("EL")) w = 1.5;     //elevator, weight = 1.5
                else if (newName.ToUpper().Equals("RP")) w = 1.5;  //ramp, weight = 1.5
                else if (newName.ToUpper().Equals("ST")) w = 2;   //stairs, weight = 2.0
                src = 1;
                if (listRoomsID.ContainsKey(specRooms[i]))
                  src = listRoomsID[specRooms[i]];
                targ = 1;
                if (listRoomsID.ContainsKey(specRooms[j]))
                  targ = listRoomsID[specRooms[j]];

                writer.WriteLine(src + ";" + targ + ";Undirected;" + lastName + newObj +
";;" + w.ToString());
                j = specRooms.Count;
              }
            }
          }
        }
      }
    }

    // Summary:
    //   Verify if the room contains one of wall hosting an opening
    private bool isWallInRoom(Room r, Dictionary<ElementId, OpeningInfo> openingsList)
    {
      IList<IList<Autodesk.Revit.DB.BoundarySegment>>loops=r.GetBoundarySegments(new
SpatialElementBoundaryOptions());
      foreach (IList<Autodesk.Revit.DB.BoundarySegment> loop in loops)
      {
        foreach (Autodesk.Revit.DB.BoundarySegment bs in loop)
        {
          Element e = bs.Element;
          if (e != null && openingsList.ContainsKey(e.Id))
          {
            return openingsList[e.Id].setRoom(r);
          }
        }
      }
      return false;
    }

    // Summary:
    //   create a dictionary of walls with openings
    private Dictionary<ElementId, OpeningInfo> getOpeningsInfo(Document doc)
    {
      //lists all openings in the active document
      FilteredElementCollector collector = new FilteredElementCollector(doc);
      Dictionary<ElementId, OpeningInfo> result = new Dictionary<ElementId, OpeningInfo>();
      ICollection<ElementId>          openings          =         collector.WherePasses(new
ElementClassFilter(typeof(Opening))).ToElementIds();
      foreach (ElementId e in openings)
      {
        Opening open = doc.GetElement(e) as Opening;
        try
        {
          //returns only openings hosted by a wall
          if (open.Host != null && doc.get_Element(open.Host.Id) is Wall)
          {
            Wall w = doc.get_Element(open.Host.Id) as Wall;
            result.Add(w.Id, new OpeningInfo(open, w));
          }
        }
        catch (Exception Exception) { }
      }
      return result;

    }
  }
```

D3 - DRoomlink.cs

```
using System;
using System.Collections.Generic;
using System.Linq;
using System.Text;
using System.Threading.Tasks;
using Autodesk.Revit.DB;
using Autodesk.Revit.DB.Architecture;

namespace Util
{
  // Summary:
  //   Class to store info about room links
  class RoomLink
  {
    Room _room1;
    Room _room2;
    Element _roomSep;
    bool _notSet;

    public RoomLink(Element el, Room r1, Room r2)
    {
      _roomSep = el;
      _room1 = r1;
      _room2 = r2;
      _notSet = true;
    }
    public bool isNew()
    {
      return _notSet;
    }
// Returns:
    //   returns a String with info about this room link and weight=1.0
    public String writeFile(Dictionary<ElementId, int> listID)
    {
      int src = 1, targ = 1;
      if (_room1 != null && listID.ContainsKey(_room1.Id))
        src = listID[_room1.Id];
      if (_room2 != null && listID.ContainsKey(_room2.Id))
        targ = listID[_room2.Id];
      return  src  +  ";"  +  targ  +  ";Undirected;"  +  _roomSep.Id.ToString()  +
";RoomSeparator;1.0";
    }
    // Summary:
    //   function to verify if room links are equals
    //
    // Returns:
    //   true if link in parameter is equal to current one
    public bool isEqual(OpeningInfo o)
    {
      try
      {
        if    ((_room1.Id.IntegerValue    ==    o.getR1().Id.IntegerValue    &&
_room2.Id.IntegerValue == o.getR2().Id.IntegerValue) ||
          (_room1.Id.IntegerValue     ==     o.getR2().Id.IntegerValue     &&
_room2.Id.IntegerValue == o.getR1().Id.IntegerValue))
        {
          _notSet = false;
        }
      }
      catch (Exception e) { }
      return _notSet;
    }
  }
}
```

D4 - OpeningInfo.cs

```
using System;
using System.Collections.Generic;
using System.Linq;
using System.Text;
using System.Threading.Tasks;
```

```
using Autodesk.Revit.DB;
using Autodesk.Revit.DB.Architecture;

namespace Util
{
// Summary:
  //  Class with openings informations. Stores the rooms connected by the opening
  class OpeningInfo
  {
    Opening _open;
    Wall _hostWall;
    Room _room1;
    Room _room2;

    public OpeningInfo(Opening open, Wall host)
    {
      _open = open;
      _hostWall = host;
      _room1 = null;
      _room2 = null;
    }
    // Summary:
    //  Sets the room for the opening
    //
    // Returns:
    //   true if room was set; false otherwise
    public bool setRoom(Room r)
    {
      if ((_room1 == null && _room2 == null) ||
        (_room1  ==  null  &&  (_room2  !=  null  &&  _room2.Id.IntegerValue  !=
r.Id.IntegerValue)))
      {
        _room1 = r;
        return true;
      }
      else  if  (_room2  ==  null  &&  (_room1  !=  null  &&  _room1.Id.IntegerValue  !=
r.Id.IntegerValue))
      {
        _room2 = r;
        return true;
      }
      else  if  ((_room1  !=  null  &&  _room1.Id.IntegerValue  ==  r.Id.IntegerValue)  ||
(_room2 != null && _room2.Id.IntegerValue == r.Id.IntegerValue))
      {
        return true;
      }
      else
      {
        return false;
      }
    }

    public Room getR1() { return _room1; }
    public Room getR2() { return _room2; }
    // Summary:
    //  prepare info to write into file
    //
    // Returns:
    //   String - connection info for the opening, (weight=1.0)
    public String writeFile(Dictionary<ElementId,int> listID)
    {
      int src=1, targ=1;
      if (_room1 != null && listID.ContainsKey(_room1.Id))
        src = listID[_room1.Id];
      if (_room2 != null && listID.ContainsKey(_room2.Id))
        targ = listID[_room2.Id];
      return src + ";" + targ + ";Undirected;" + _open.Id.ToString() + ";;1.0";
    }
// Returns:
    //   true if both rooms are not null
    public bool isComplete()
    {
      return (_room1 != null && _room2 != null);
    }
  }
}
```

All external materials are explicit quoted directly in the text or through a footnote.

In faith,

Ing. Vincenzo Donato